Spacecraft Vibration Control

A Tutorial

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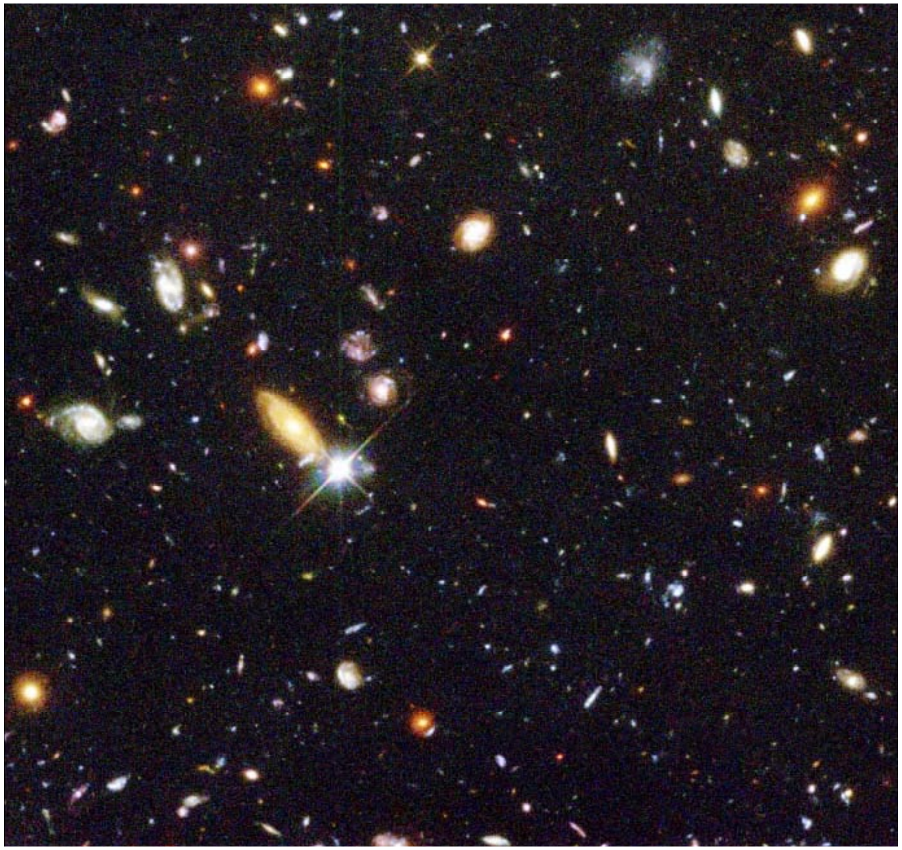
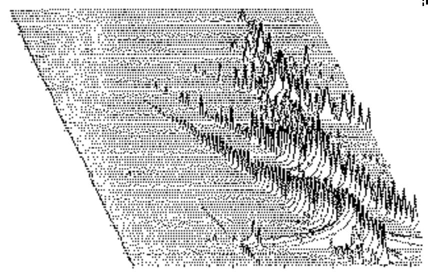
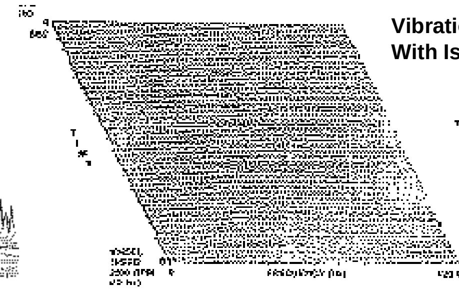
Hubble Space Telescope



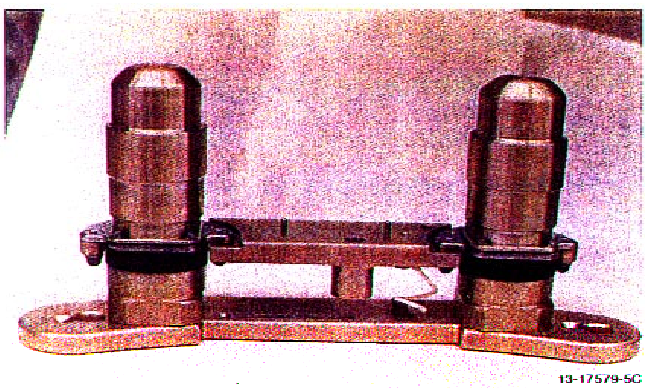
Disturbance:
  Reaction wheel unbalance
Performance:
  $\theta_{RMS} < .007$ arcsec

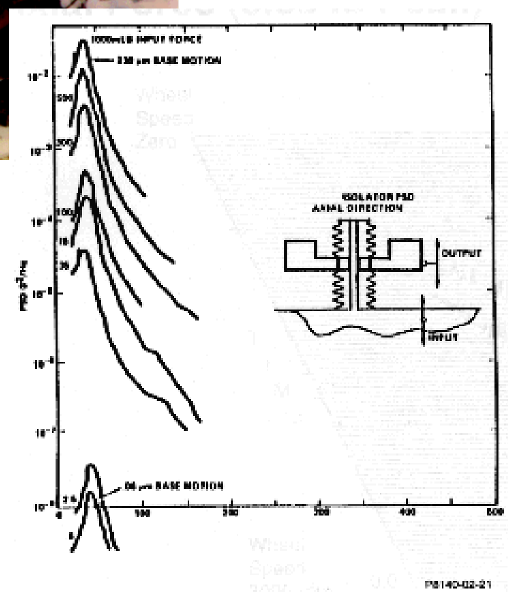
Solution: RWA Isolation



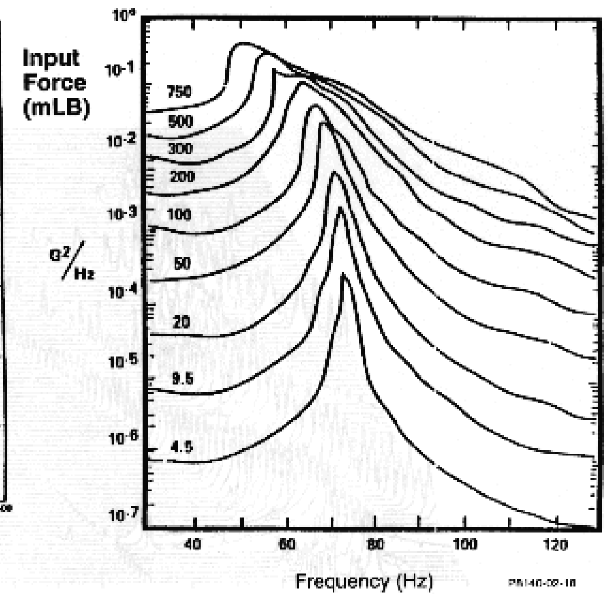


Vibration Force
With Isolation





Viscous Isolator

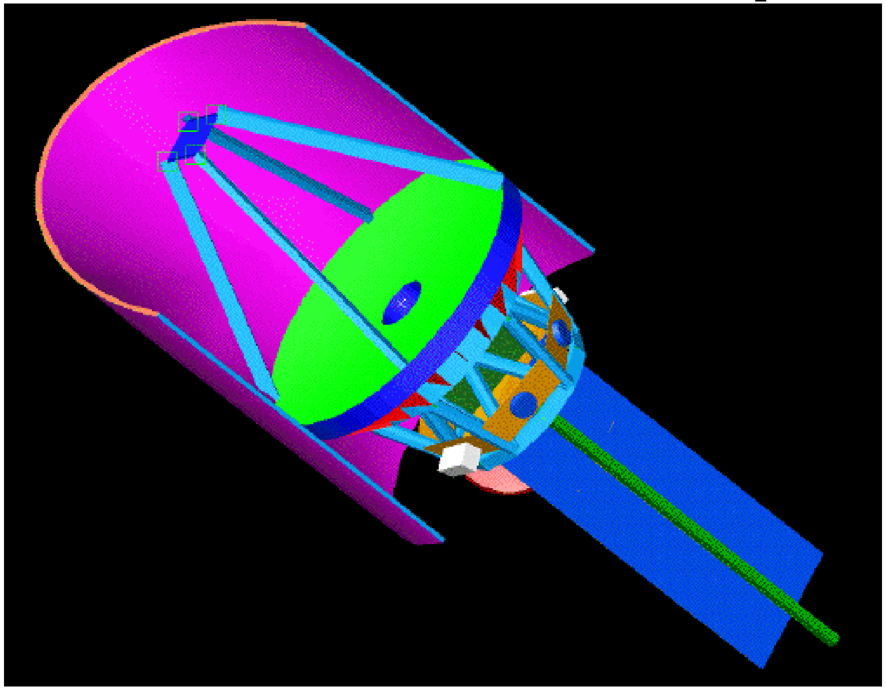


Wire Rope Isolator

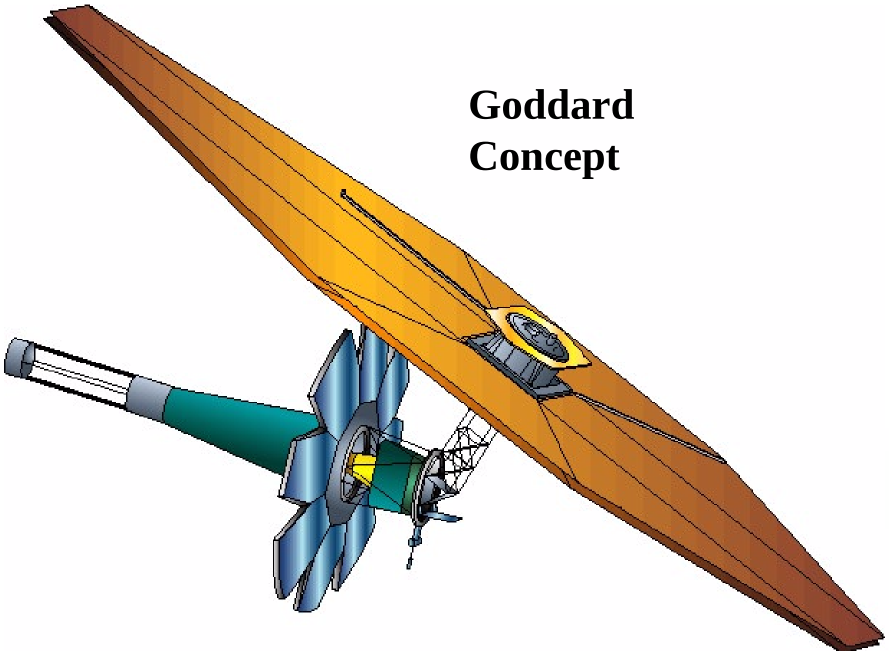
Precision Spacecraft

- Optical Payloads
  - astronomical telescopes
  - interferometers / sparse optical arrays
  - earth imaging
  - lasercom intersatellite links
  - beam forming
- RF Payloads
  - radar interferometry
- Micro-gravity facilities

Next Generation Space Telescope (NGST)- Lockheed Martin Concept



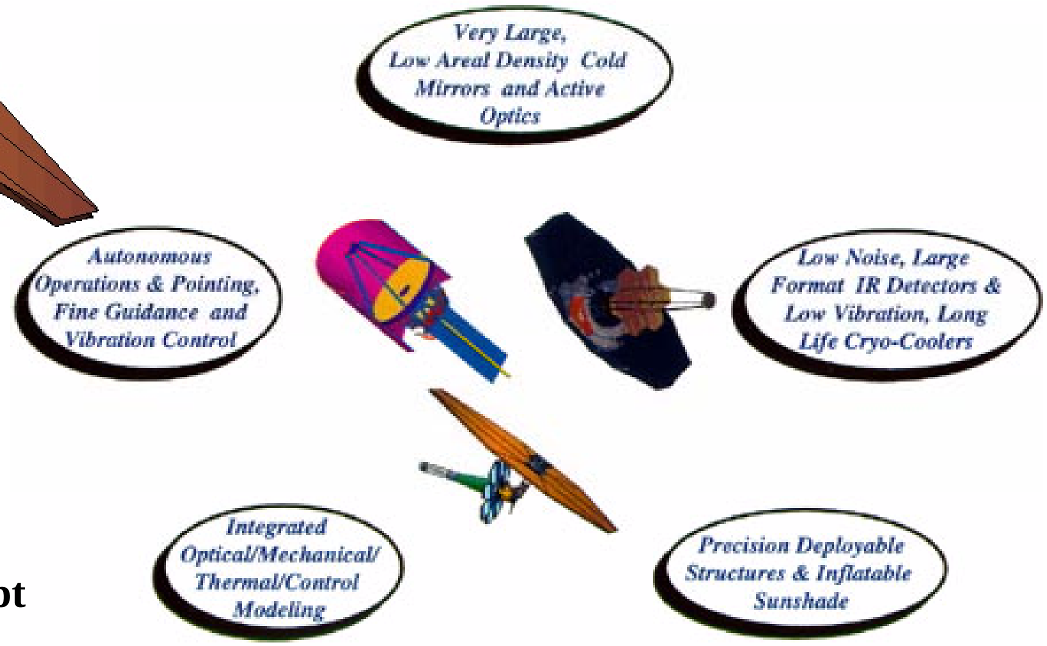
Astronomical Telescopes

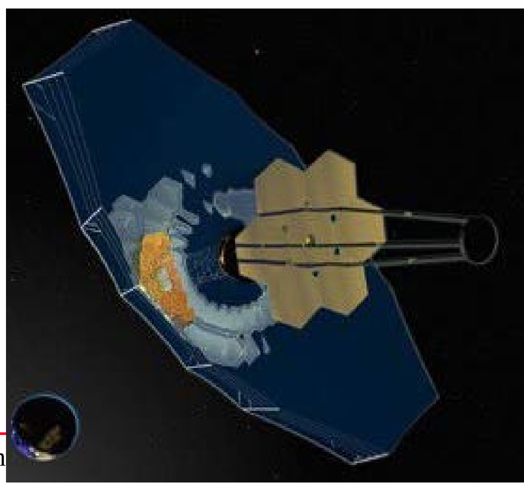


Goddard Concept

Next Generation Space Telescope (NGST)

Disturbance: RWAs, cryo-coolers
Performance: LOS < .006 arcsec



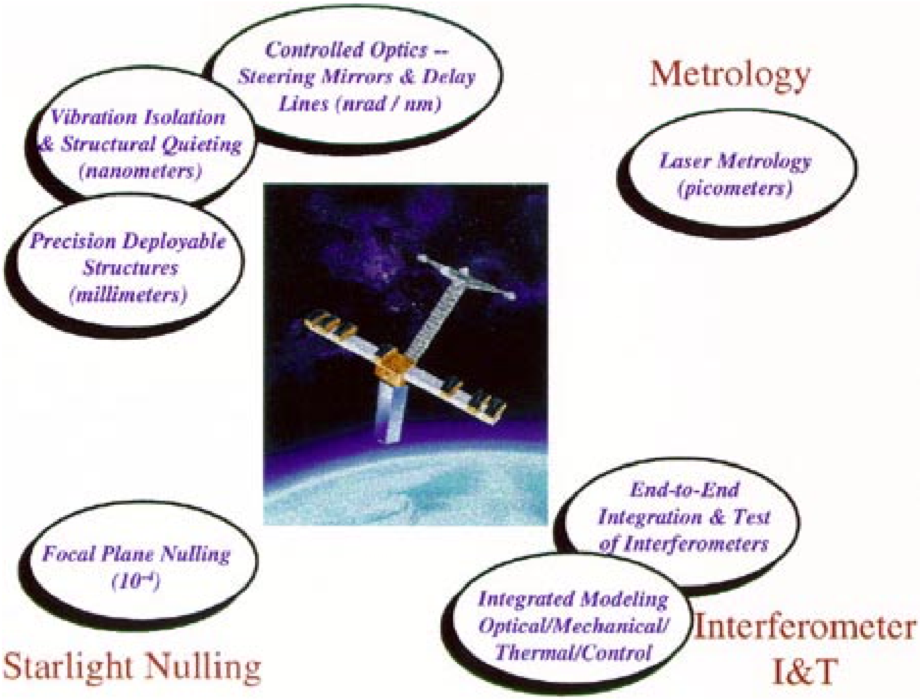


TRW Concept

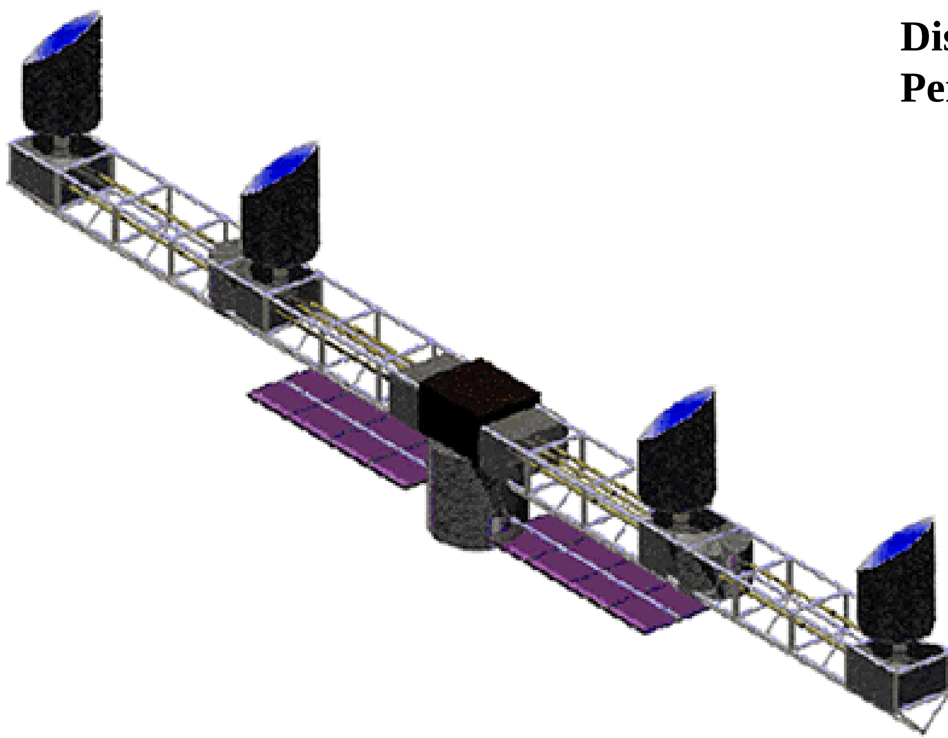
Interferometers

Stellar Interferometry Mission (SIM)

Disturbance: RWAs, optics motion
Performance: OPD < 1 nm RMS

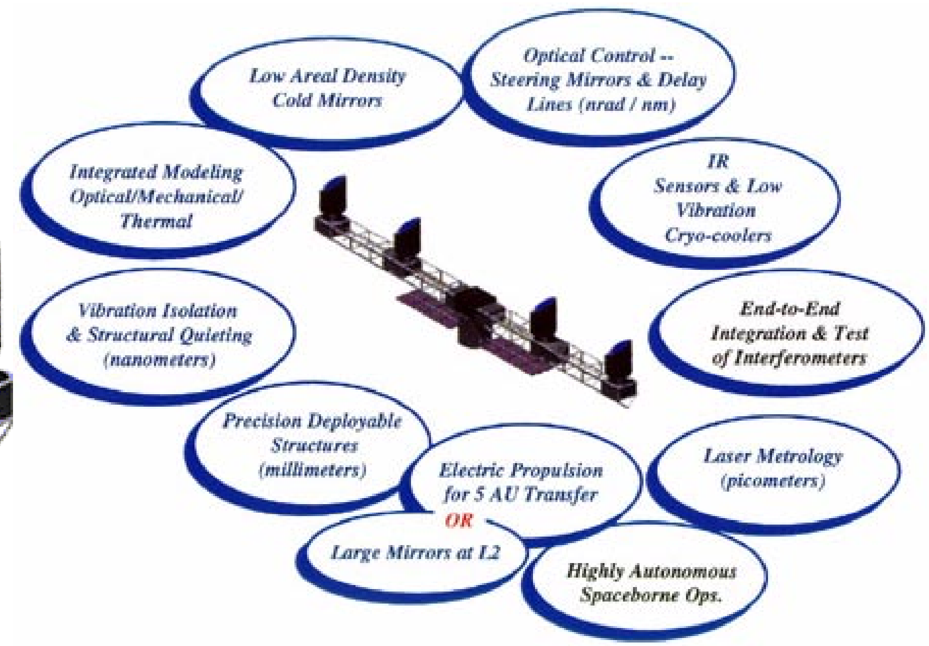


Future Observatories

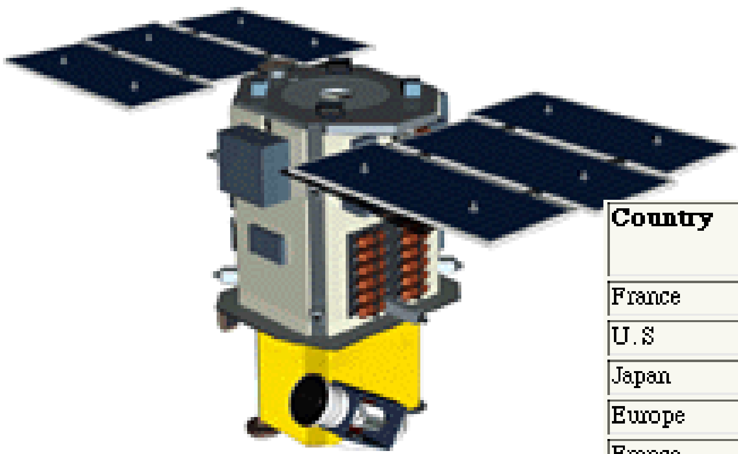


Terrestrial Planet Finder (TPF)

Disturbance: Slews, RWAs?
Performance: OPD < 1 nm RMS
& LOS < .01 arcsec



Commercial Earth Imaging



Quickbird

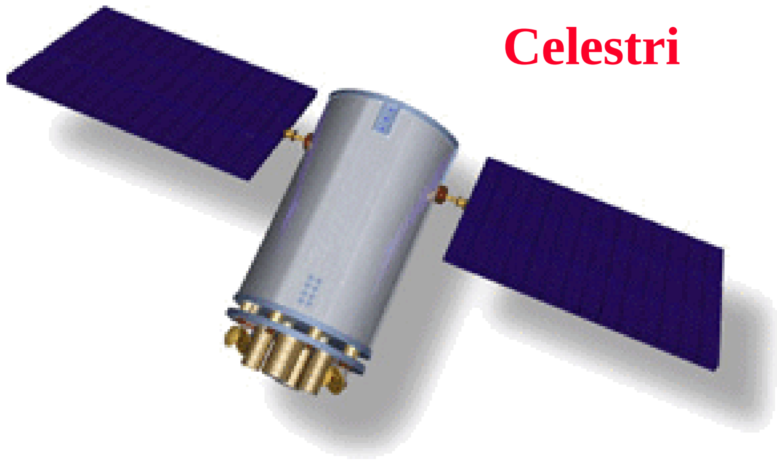
Disturbance: RWAs, SADs
Performance: LOS < 0.2 μrad

Planned Systems ('97-'04)

Country	Owner /OBJ (1)	Program	Sched Date	Inst Type (2)	Resolution in Meters		
					P	M	R
France	G/O	Spot 5B	'04	P/M	5		
U.S	G/O	EOS AM-2 / L-8	'04	P/M	10	30	
Japan	G/O	ALOS	'02	P, M, R	2.5	10	10
Europe	G/R	ENVISAT	'99	R			30
France	G/O	Spot 5A	'99	P/M	5	10	
India	G/O	IRS-1D	'99	P/M	10	20	
U.S.	C/O	GDE	'98	P	1		
U.S.	C/O	OrbView	'98	P/M	1,2	8	
U.S.	C/O	Resource 21	'98	M		10, 100	
U.S.	C/O	Space Imaging	'98	P/M	1	4	
Korea	G/O	KOMPSAT	'98	P/M	10	10	
U.S. / Japan	G/O	EOS AM-1	'98	M	15	15	
U.S	G/O	Landsat 7	'98	P/M	15	30	
Europe	G/O	ENVISAT	'98	R			30
U.S.	C/O	Space Imaging	'97	P/M	1	4	
France	G/O	Spot 4	'97	P/M	10	20	
U.S.	C/O	EarthWatch	'97	P/M	1	4	
U.S.	C/O	EarthWatch	'97	P/M	3	15	
U.S.	G/E	CTA Clark	'97	P/M	3	15	

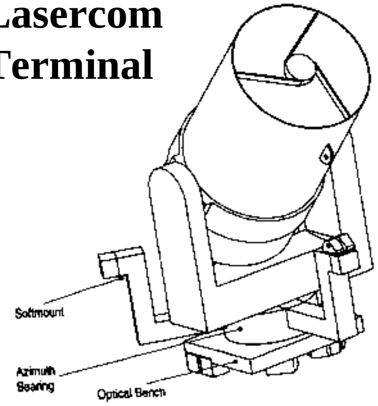
Commercial Communications Constellations

Celestri



- Peak DC power 13.6 kW
- Average DC power 4.6 kW
- Mission life 8 yrs. (10 yrs. expendables)
- Stabilization & positioning sensing 3 axis stabilized; GPS
- Length 12.7 meters (41.67 ft.)
- Wet mass 3,100 kg (6,834 lbm)
- Dry mass 2,500 kg (5,512 lbm)
- Propellant 600 kg (1,323 lbm)
- User service links -- up 432
- User service links -- down 260
- Frequency -- Earth to space 28.6-29.1 and 29.5-30.0 GHz
- Frequency -- space to Earth 18.8-19.3 and 19.7-20.2 GHz
- Intersatellite links 6
- **Intersatellite link rate 4.5 Gbps**
- Satellite switch rate 17.5 Gbps
- Aggregate data rate 8.7 Gbps

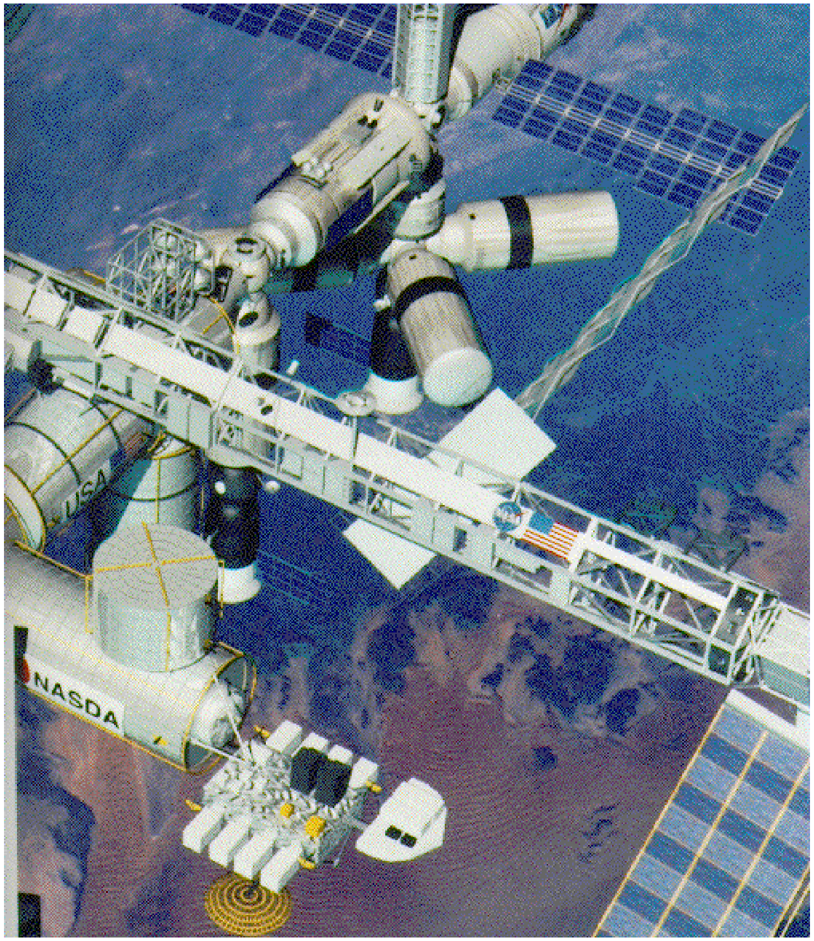
Lasercom Terminal



Teledesic

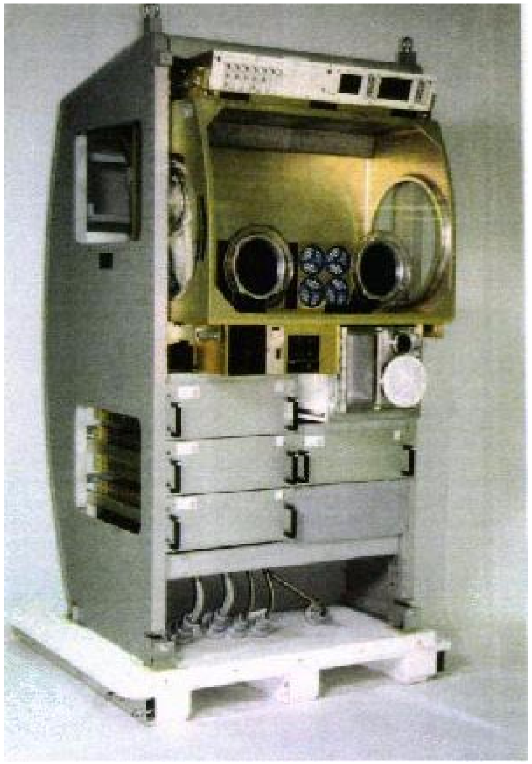
Disturbance:
RWAs, SADs,
UL/DL Antennas
Performance:
Lasercom LOS
< 1 μrad

Micro-gravity Facilities



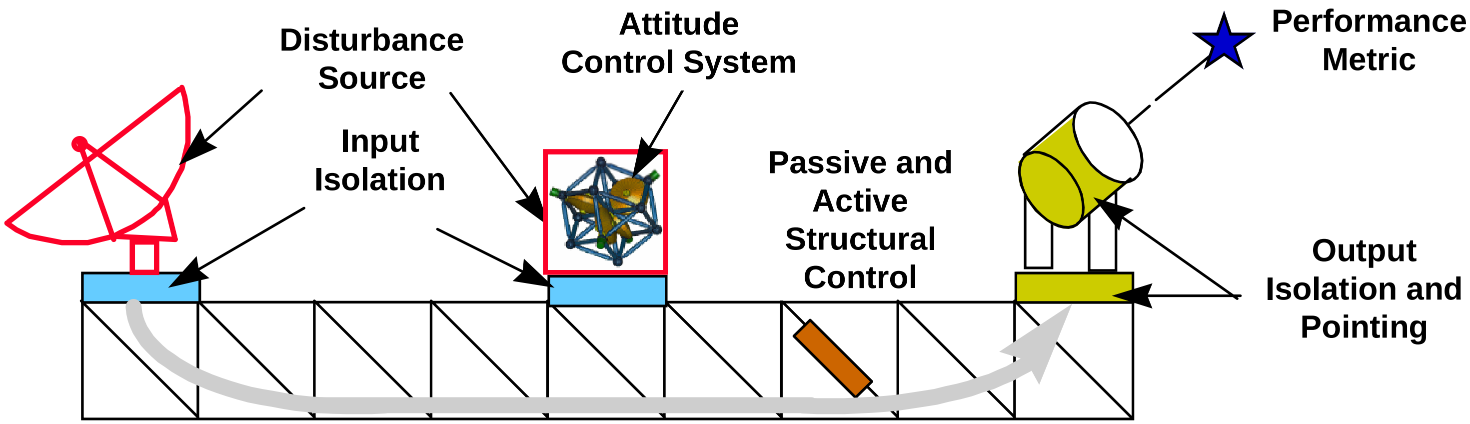
Space Station Experiment Rack

Disturbance: crew, pump/fans,
rotating mechanisms
Performance: jitter < 1 μg

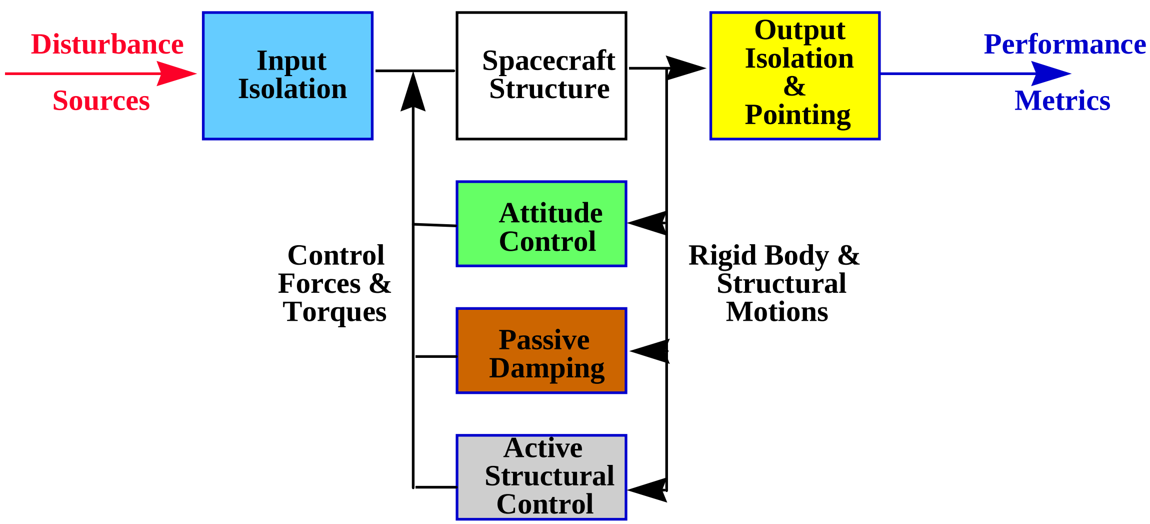


Disturbance to Performance

Spacecraft Vibration Control.. A Systems Problem



Disturbance to Performance Path



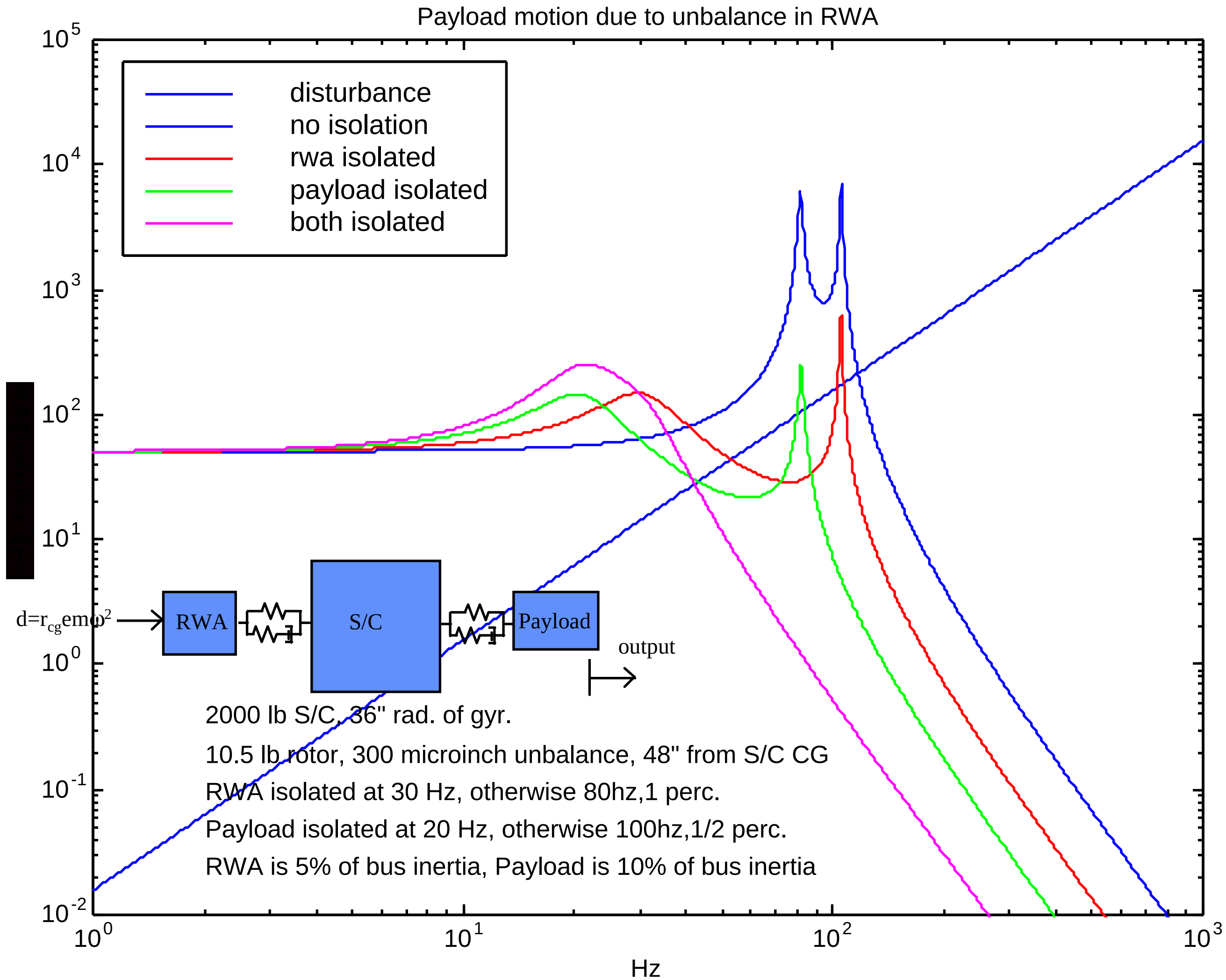
Spacecraft Disturbances

- Momentum Devices
  - Reaction Wheel (RWAs)
  - Momentum Wheel (MWAs)
  - Control Moment Gyroscopes (CMGs)
- Mechanisms
  - Solar Array Drives (SADs)
  - Antenna pointing gimbals
  - Rotating and slewing payloads
- Payload induced
  - cryo-cooler
  - moving components
- Commanded Slews
  - body re-target
  - appendage slew
- Thermal Effects
  - thermal snap
  - non-zero CTE
  - micro-dynamics
- Manned
  - crew push-off
  - exercise equip.
  - pumps/fans

Spacecraft Modeling

- Choosing the correct model fidelity is key
- Closely consider disturbance and performance definitions
- Must have:
  - correct rigid body mass/inertia
  - good first mode frequency and modal participation
  - about right modal density (exact modes not needed)
  - assume half percent damping if no damping treatment
- Options
  - Full blown FEM, usually not available early in design
  - Conceptual design FEM, trusses and plates
  - “Stick” model, beams and masses, misses local modes
  - Rigid body, may add “Q” effect of modes

Simplest Disturbance to Performance Model

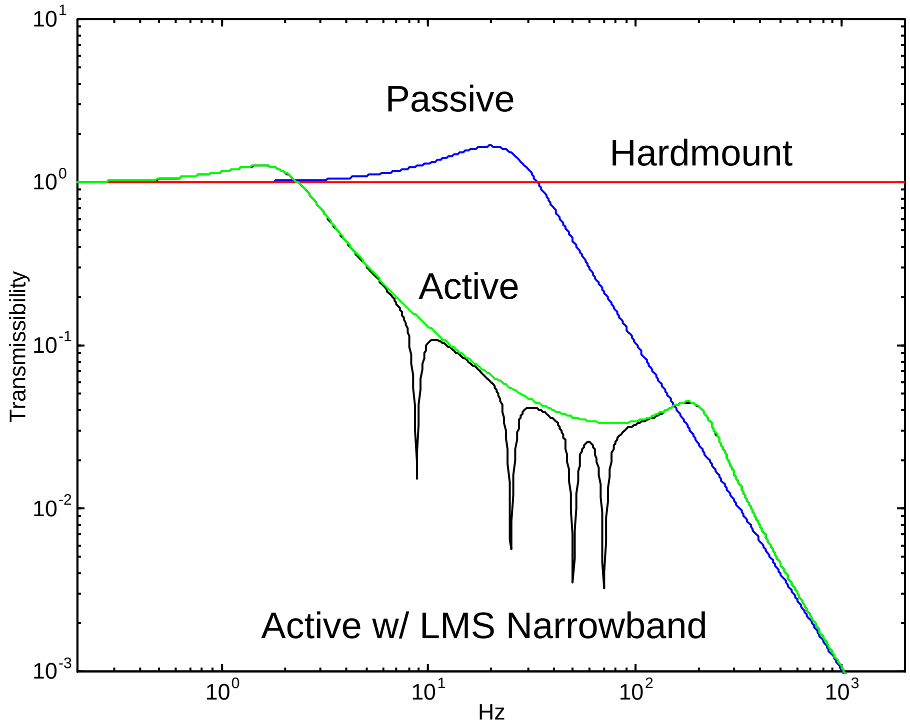


Spacecraft Performances

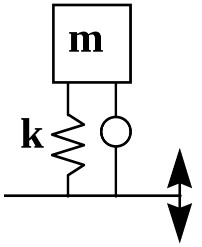
- **Line of Sight**
  - **Definition of accuracy, smear, and jitter**
  - **RMS**
  - **Effect of time integration**
  - **Effect of optical servos (fast steering mirrors)**
  - **Image motion compensation (IMC)**
  - **Mode of operation (acquisition, coarse/fine pointing)**
- **Optical Pathlength Difference**
  - **RMS causes blur on fringe detector**
  - **Effect of metrology and optical delay line servos**
  - **Mode of operation (acquisition, astrometry, imaging)**
- **Microgravity**
  - **RMS**
  - **peak**

Disturbance Isolation

Input Isolation

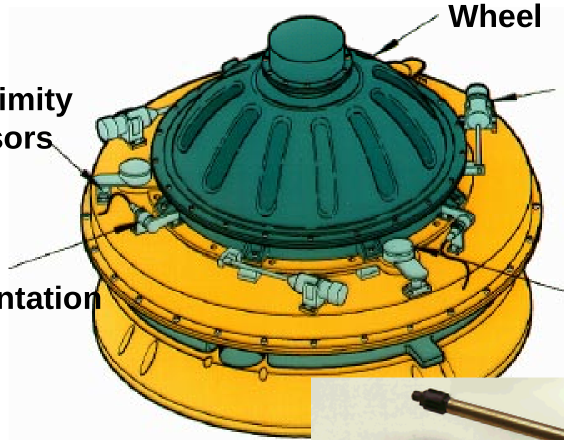


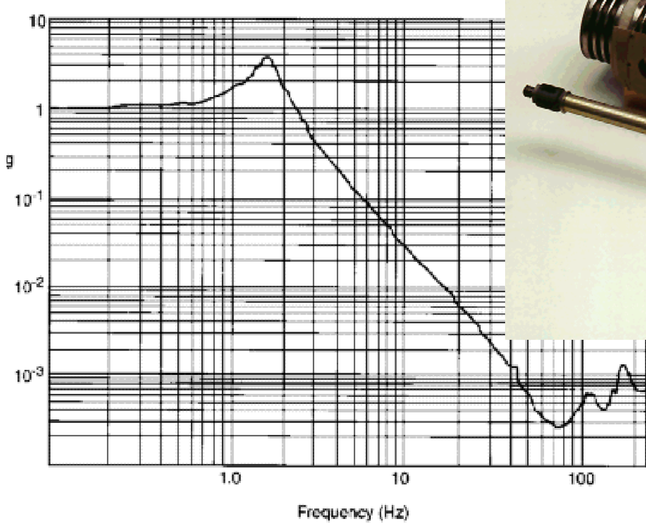
- **Passive**
  - **visco-elastic**
  - **fluid**
  - **eddy current**
- **Active**
  - **magnetic**
  - **voice-coil**
  - **smart material (piezoelectric)**
- **Hybrid**
  - **passive and active components**



$$\omega_{corner} = \sqrt{\frac{k}{m}}$$

EUREKA Isolation System





Characteristics	
Application	Gimballed Momentum Wheel Isolation
Payload Weight	225 lb
Isolation System Weight	3 lb
Element Weight	0.615 lb
Number of Elements	3
Number of Axes	3
Envelope	29 in.
Temperature Range	0 to 120 °F
Life	15 years
Isolation Performed	
• Attenuation at 100 Hz	0.0005 to 1
• Break Frequency	1.5 Hz
• Amplification	3.2 to 1
• Alignment Stability	0.05 degree
Random Vibration	Latched
Sine Wave	Latched

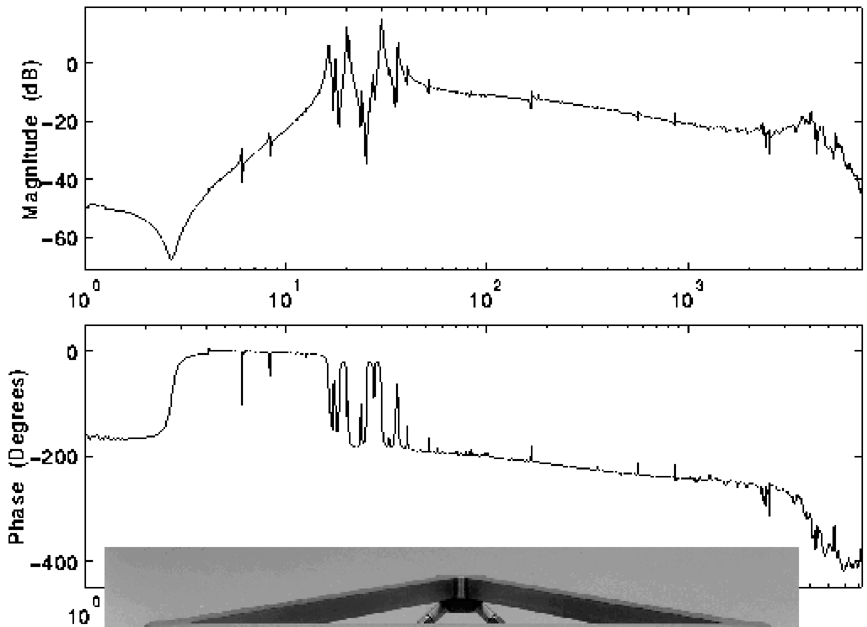
M54559/CLR

MATRA Isolation System

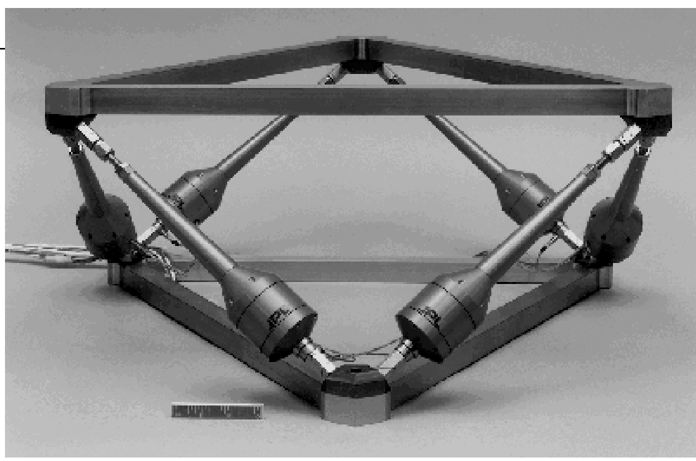
Characteristics	
Application	RWA Vibration Isolation
Payload Weight	35 lb.
Isolation System Weight	12.2 lb
Element Weight	0.75 lb
Number of Elements	6
Number of Axes	6
Envelope	20 OD x 4.5 in
Temperature Range	-15 to +65 C
Life	10 Years
Isolation Performed	
* Attenuation at 100 Hz	0.01 to 0.05
* Break Frequency	4 to 10 Hz
* Amplification	8:1
* Alignment Stability	0.05 degree
Random Vibration	19g rms
Sine Wave	12g

JPL Hexapod Isolation Results

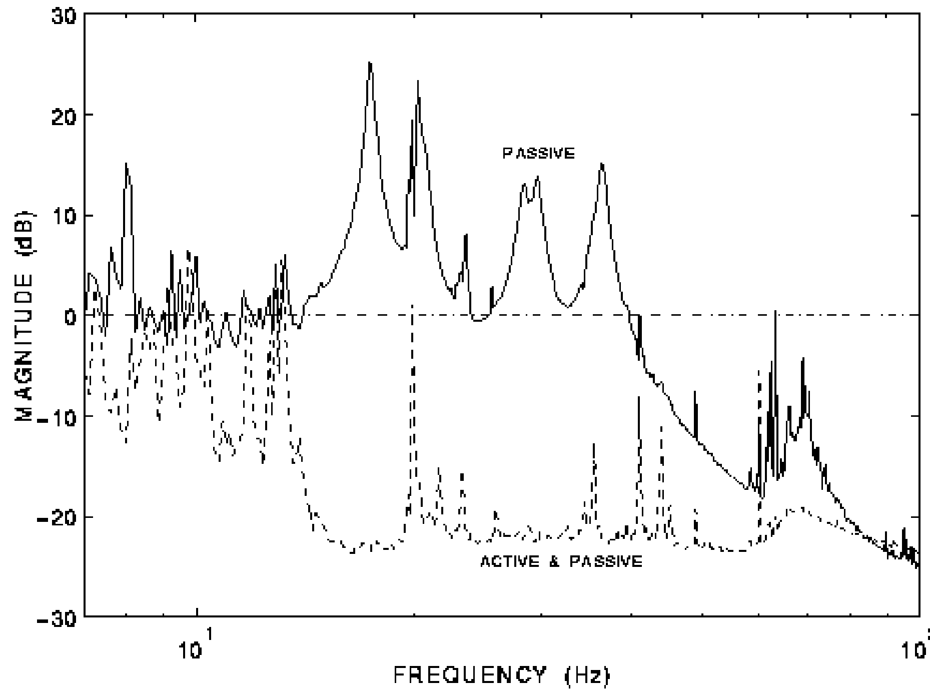
Six-axis Active Strut Hexapod
J. Spanos, Z. Rahman (JPL)



Single Strut Transfer Function



Six-axis Transmissibility

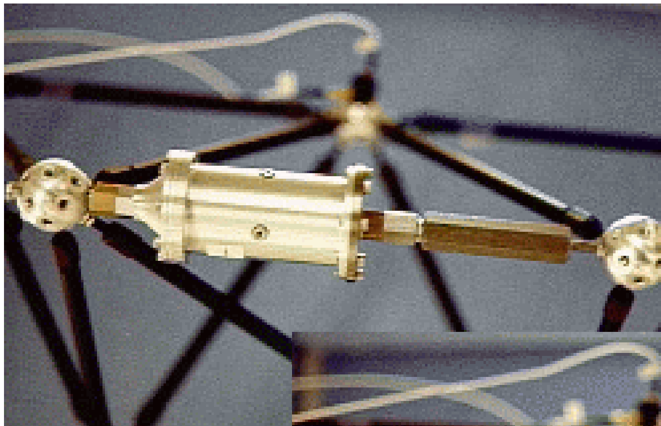


Passive & Active Structural Control

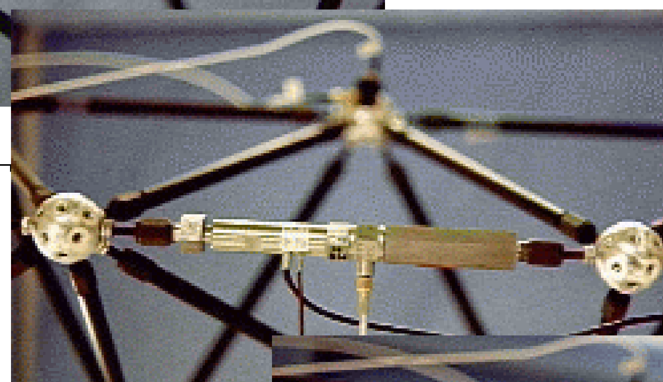
Extended Bandwidth Attitude Control and Active MIMO Structural Control

- **Push ACS bandwidth into region of flexible spacecraft modes**
  - **don’t limit bandwidth to decade below**
  - **don’t “notch” (gain stabilize) flex modes**
  - **but control (actively stiffen & damp) flex modes**
- **This is control intensive**
  - **many states in computer at high sample rates**
  - **implies high bandwidth actuators and sensors**
  - **need for good models... on-orbit ID**
- **This is a big topic**
  - **more for another day!**

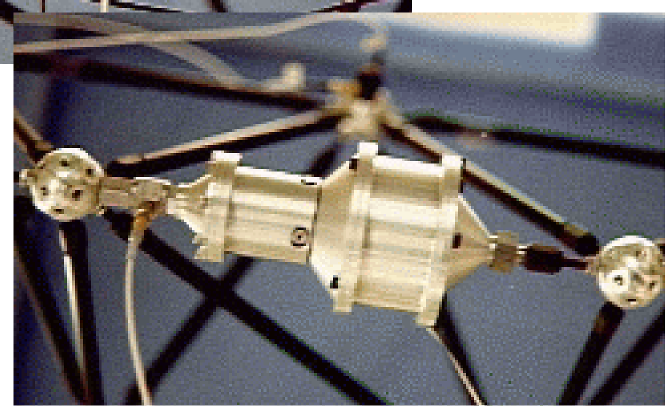
Strut Damping



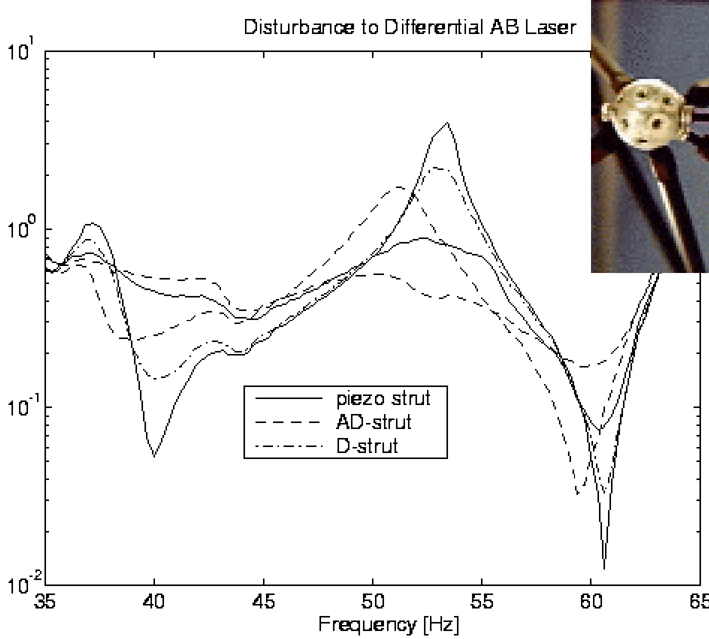
Passive
- viscoelastic
- fluid
- smart material



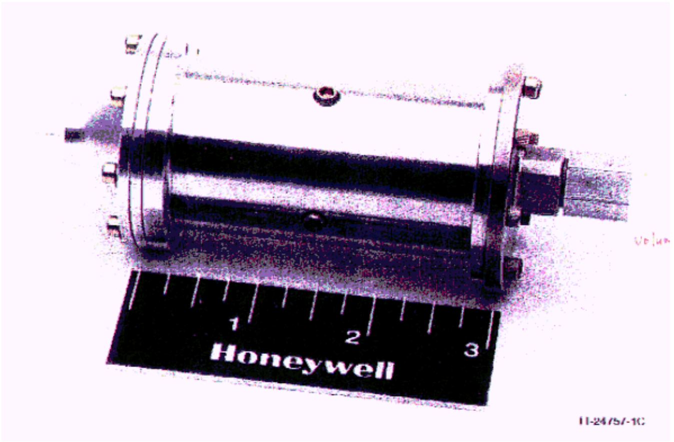
Active
- lead screw
- hydraulic
- smart material

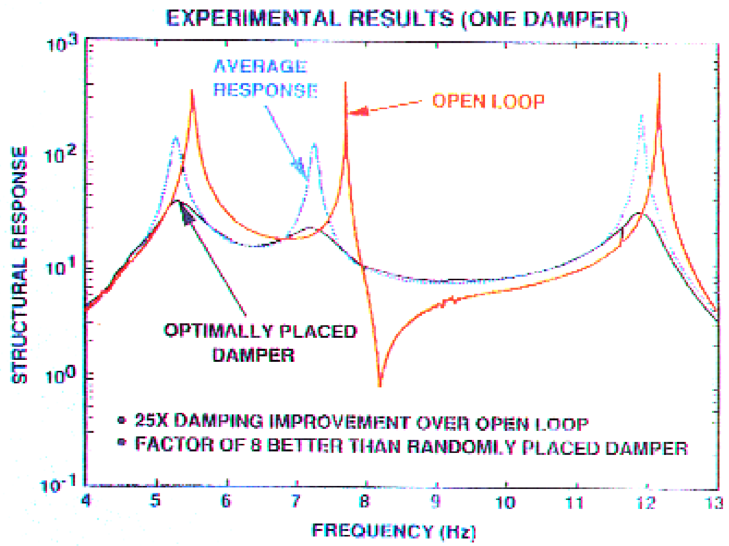


Hybrid
- passive & active components



D-Strut™ Truss Dampers





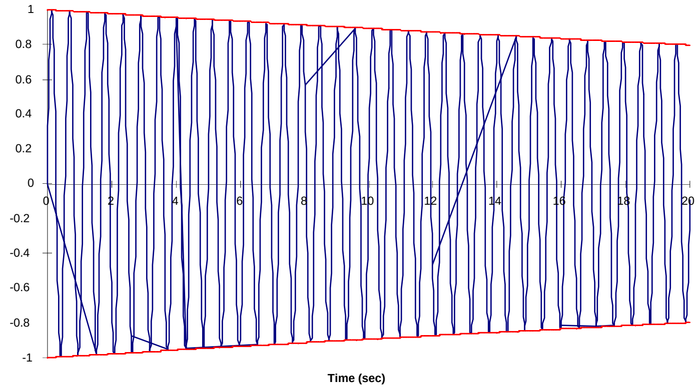
PARAMETERS

- Length -- 18.16-in (longeron), 26.44-in (diagonal)
- Maximum Diameter -- 1.5-inches (bonded version)
- Tube diameter -- 1.5-inches
- Flexural seal -- Metal Single-convolute bellows
- Weight -- 0.5-lbs plus tube, typical total 1.1-lb
- Load capacity -- greater than 500-lbs
- Static Stiffness -- family range 25000 to 60000-lb/in
- Dynamic Stiffness -- range 100,000 to 190,000-lb/in
- Damping coefficient -- 50 to 250-lb.sec/inch
-

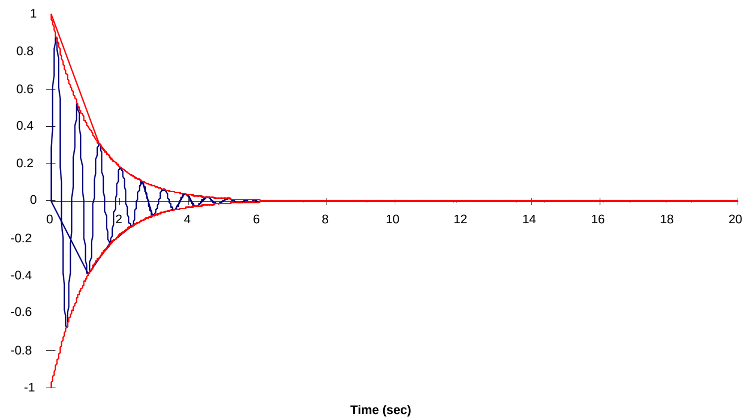
FEATURES

- Easily tuned for desired frequency and damping
- Flight qualified design and materials
- Damping linear over displacement range
- Fast settling time for pointing/tracking systems

Tuned Mass Dampers



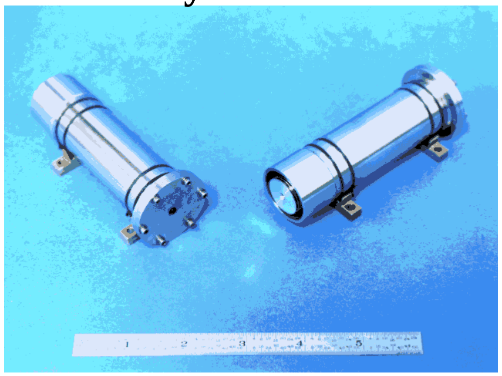
Undamped
0.1% damping
Settling time=11min
1.8 Hz

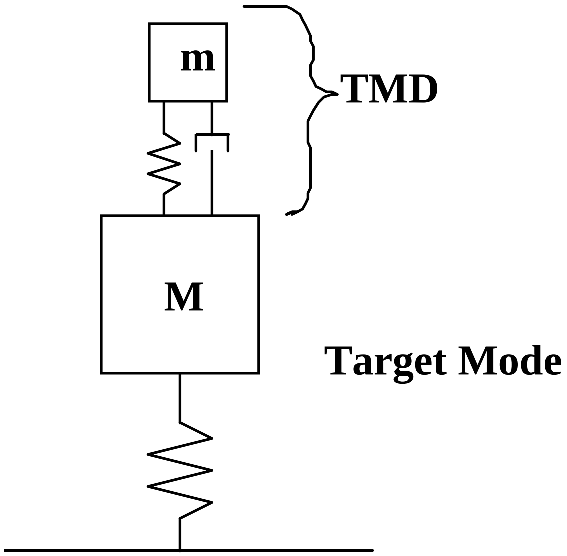


Damped
8.4% damping
Settling time=0.13 min
1.6 Hz

Shown for 22 foot boom (cantilever mode)
Total mass of devices for 2 axis=3/4 lb. in flight configuration

Honeywell TMDs



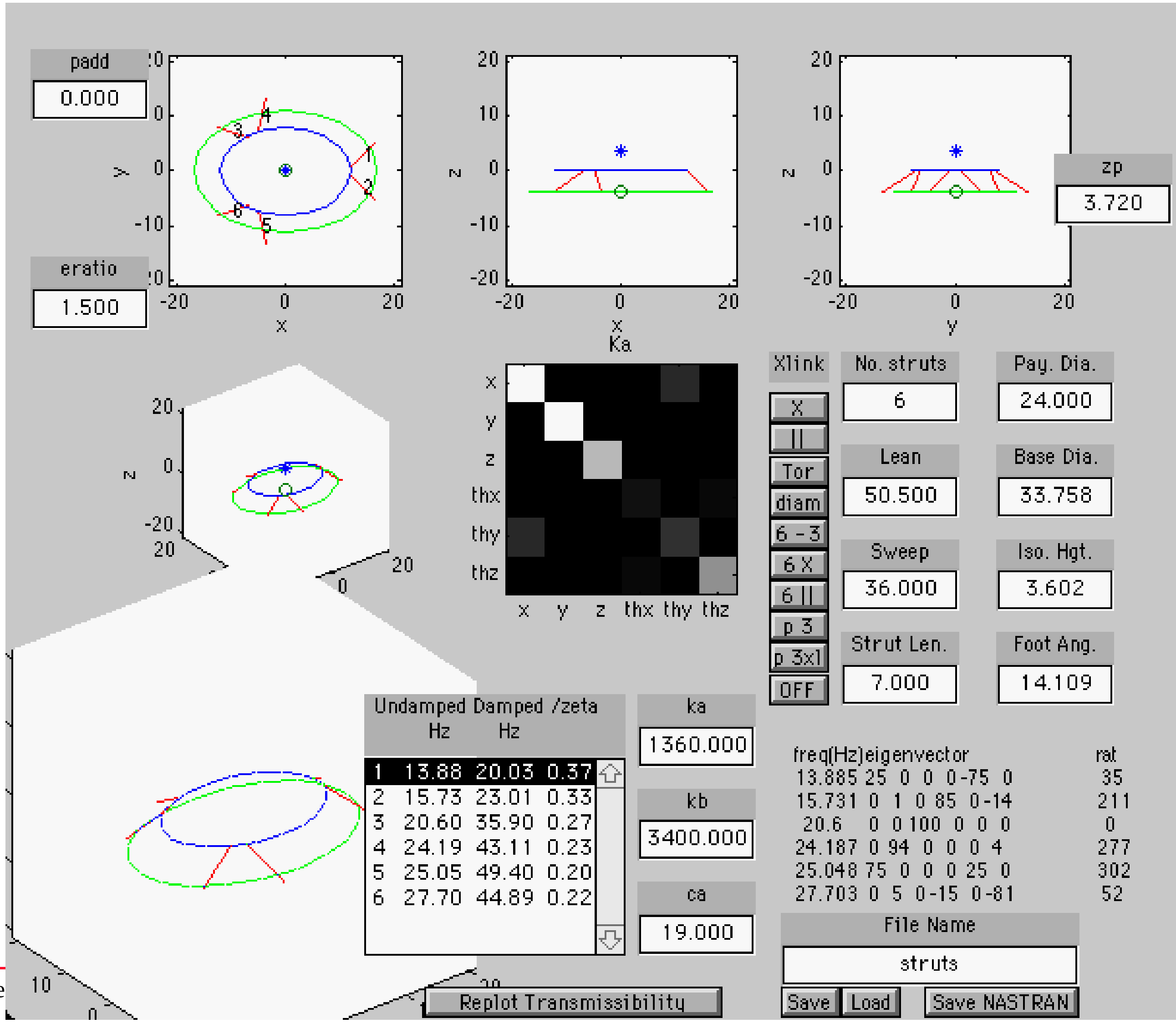


Payload Isolation and Precision Pointing

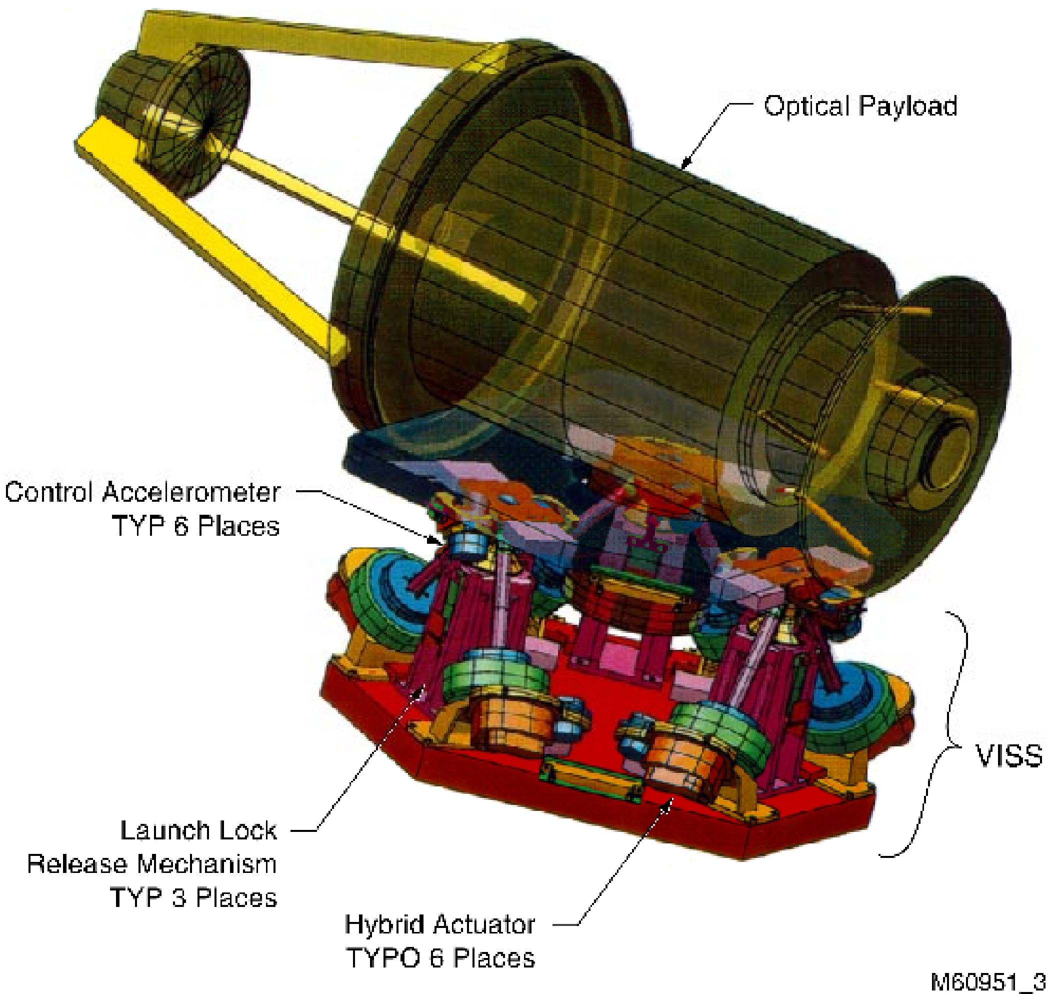
Passive Isolation of a Lasercom Terminal

- Operational isolation
  - LOS rotations critical, translations also to reduce excitation of telescope modes
  - FSM control good at low frequency but isolation required to reduce LOS jitter at high frequency
- Launch isolation
  - protect sensitive optics and mechanisms from launch vibrations
- Kinematic 6 DOF mount desirable
  - strains in S/C do not induce strains in terminal

Graphical Design Tool



The VISS and its Payload



VISS

- Vibration Isolation From Spacecraft
- Vibration Suppression of Payload Disturbances
- Payload Steering

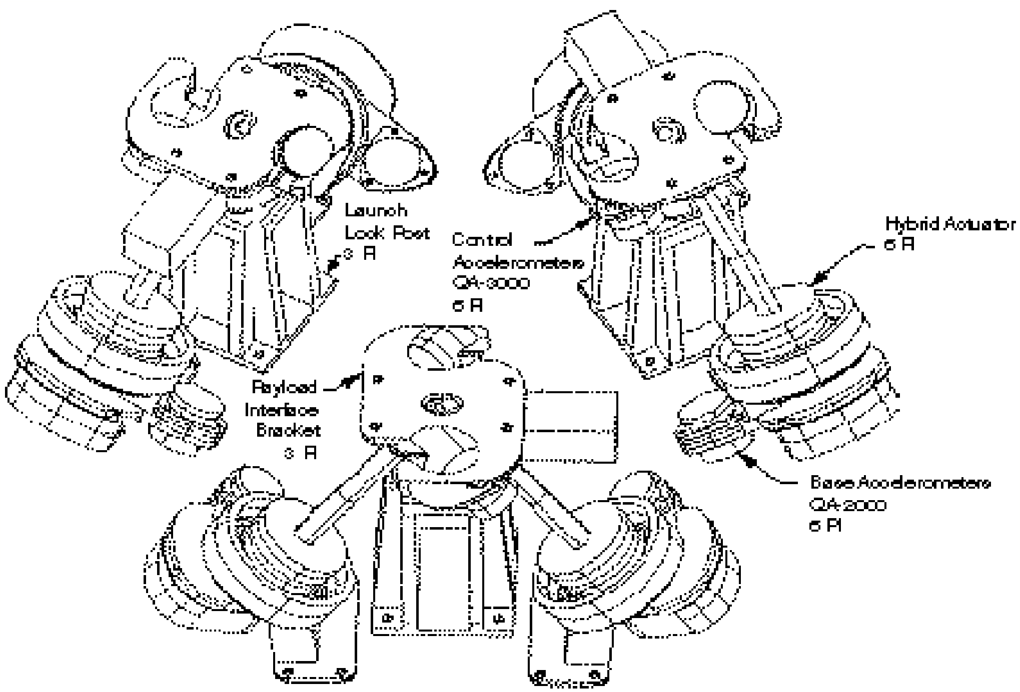
Payload

- A Medium Wave Infared Telescope
- Weight: 33 lb.
- Approximate Size: 10 in. Dia. by 25" long
- Approximate Mounting: 8" Equilateral Triangle

VISS Performance Parameters

- Vibration Isolation > 20 dB for freq. at frequencies > 5 Hz
- ± 0.3 deg Precision steering of optical payload with accuracy of 0.02 deg.
- >20dB Suppression of on-board cryocooler harmonics (55 and 110 Hz)
- System weight (including electronics): 34 lb.
- System size envelope (16.4" x 15.0" x 6.2")

VISS Hardware



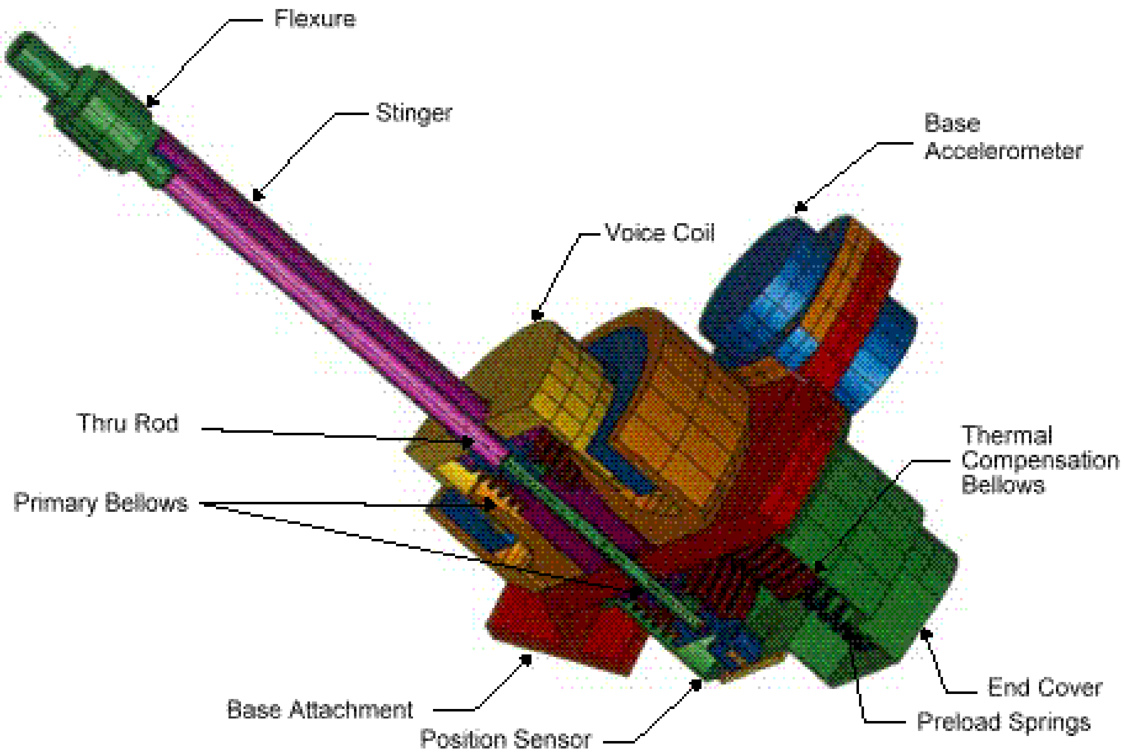
Specifications

- Electronic Box Weight: 14 lb.
- Actuator Element Weight: 2 lb.
- Total VISS System Weight: 35 lb.
- Bus Voltage: 28 VDC
- Peak Power: 50W
- Length of Strut: 8 in.
- Actuator Force: 2 lb.

Features

- **Hybrid D-Strut™ Hexapod System**
- **Passive D-Strut**
- **Voice Coil Actuators**
- **Accelerometer Control Sensors**
- **Local Placed Accelerometer Conditioning Circuits**
- **Position Sensors for Information**
- **DSP C31-based Control Electronics**
- **Shape Memory (Frangibolt) Launch Locks**

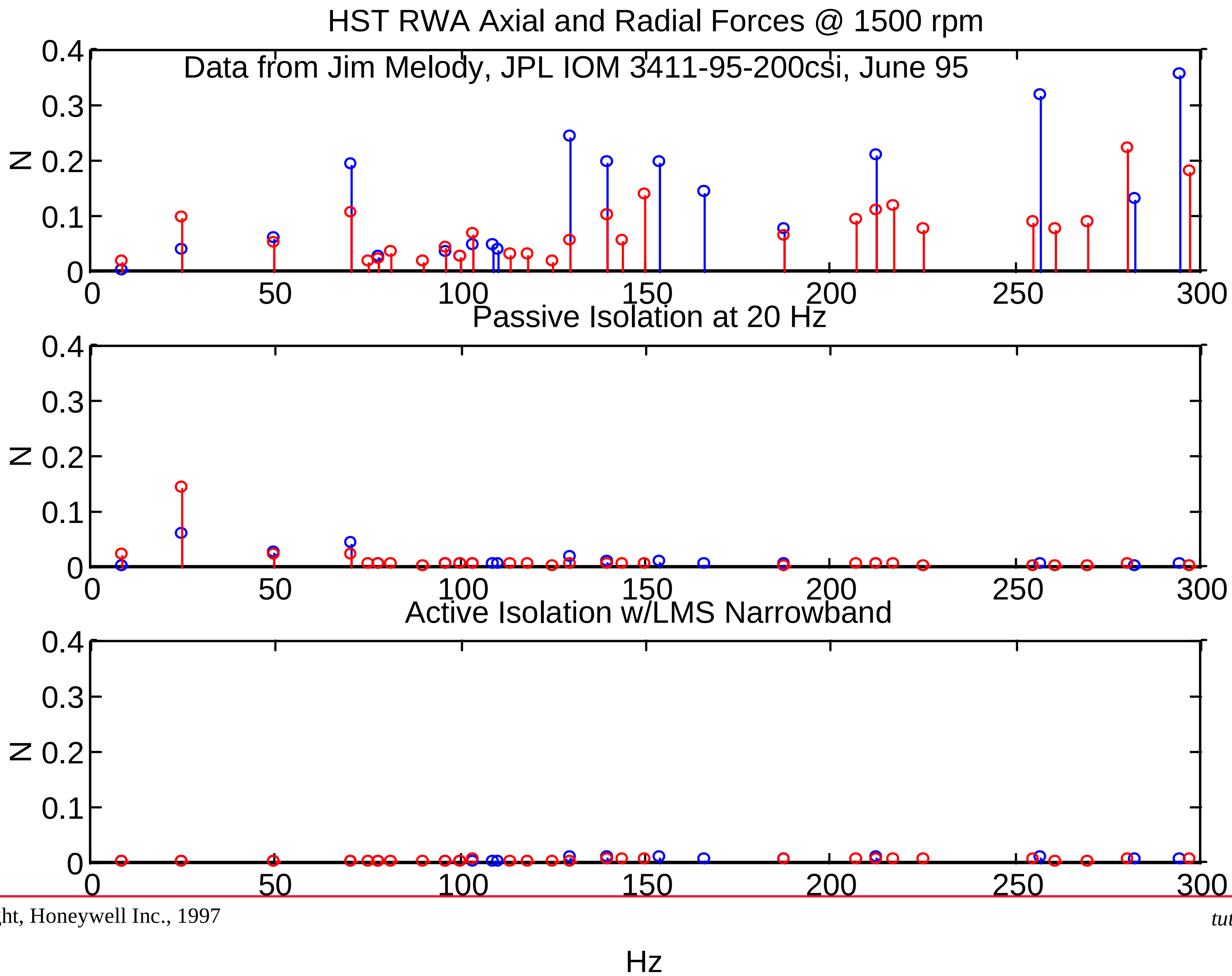
Features of Hybrid Actuator



- **Basic Elements Flight Qualified**
- **Synergistic Performance Active/Passive**
- **Large Stroke**
- **Fail-Safe Redundancy Features**
- **Adaptability**
  - **Passive Damping**
  - **Stiffness**
  - **Software Control**
- **Size, Weight, Power**

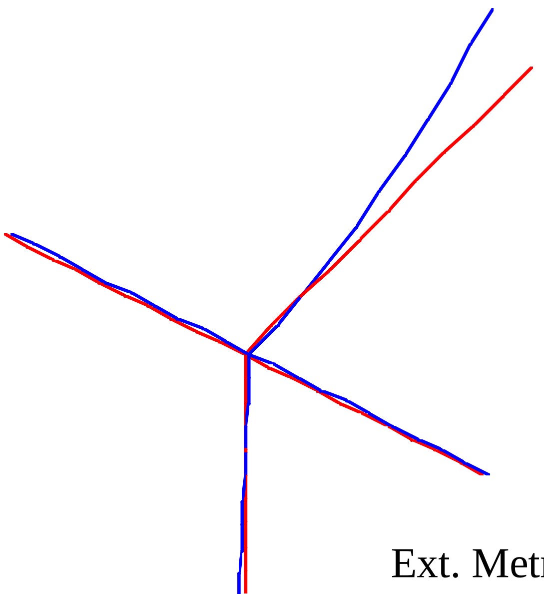
Spacecraft Vibration Modeling Example

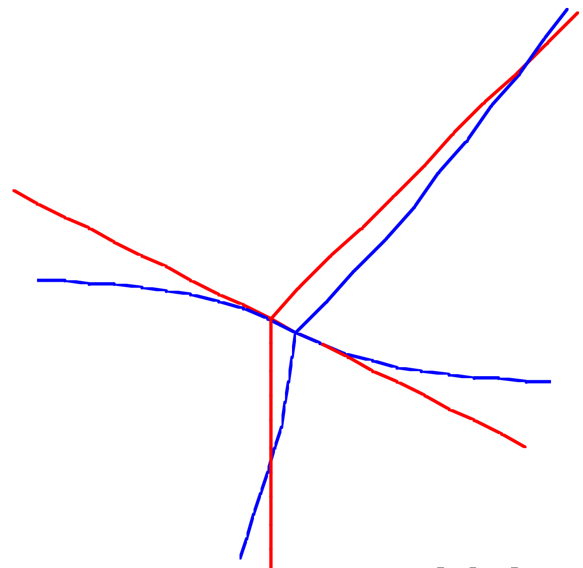
RWA Disturbance Model



FEM "Stick" Model

- **SIM Classic, mass model from baseline spreadsheet**
- **Mass: 1680 kg, Inertia: 16,700 kg-m^2 (worst axis)**
- **50 modes below 440 Hz.**

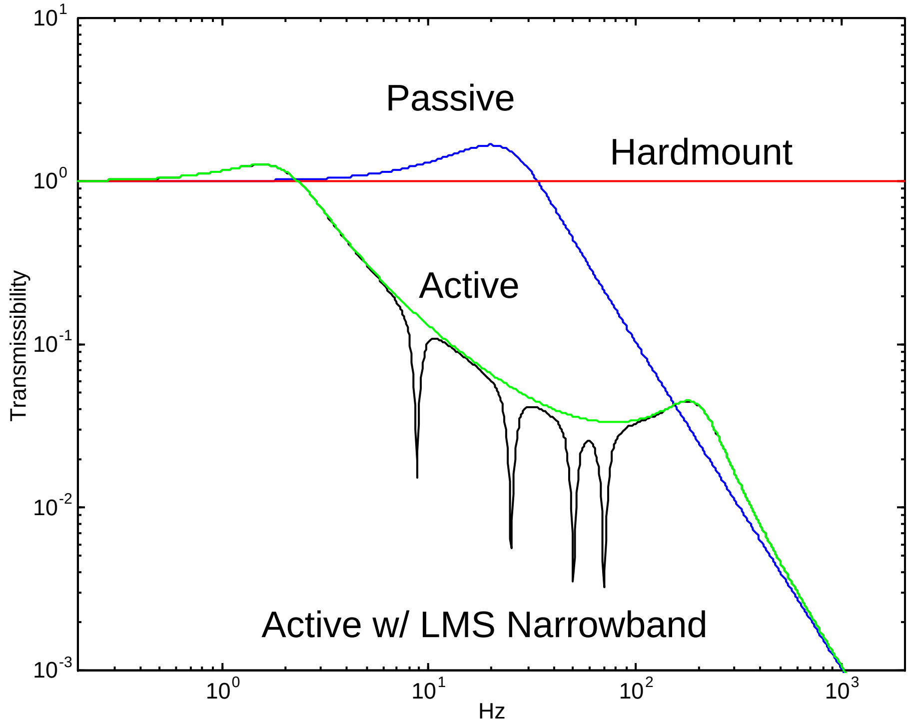


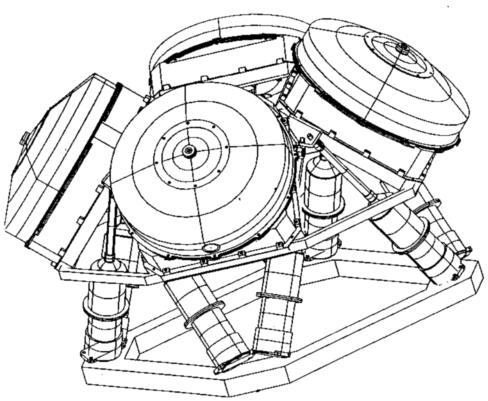


Ext. Metrology Boom
Modes at 2.5 Hz

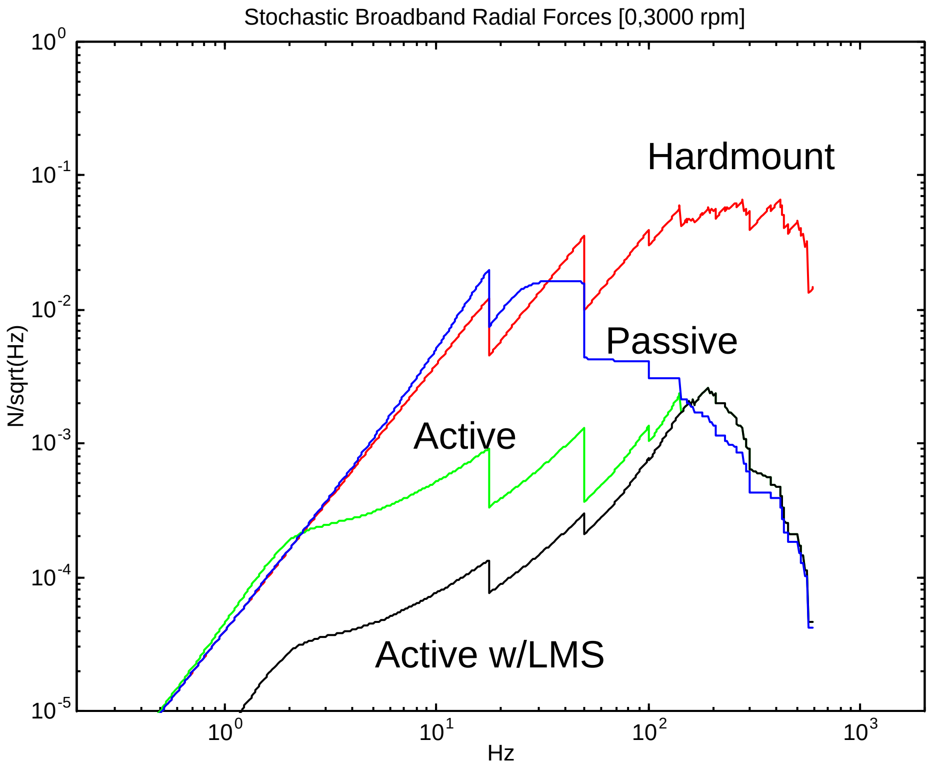
First Global/Collector
Modes at 5.9 Hz

Disturbance Isolation

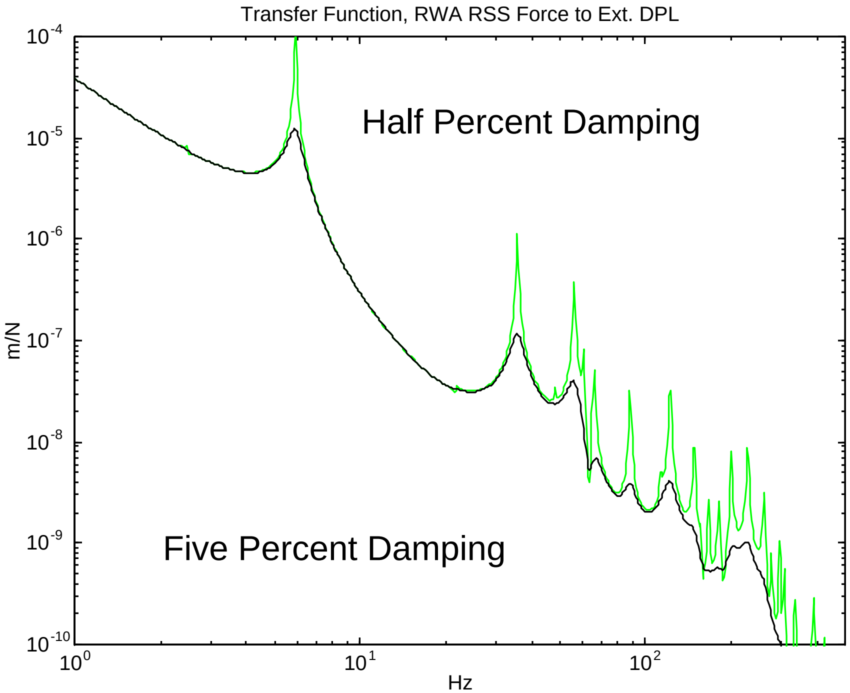




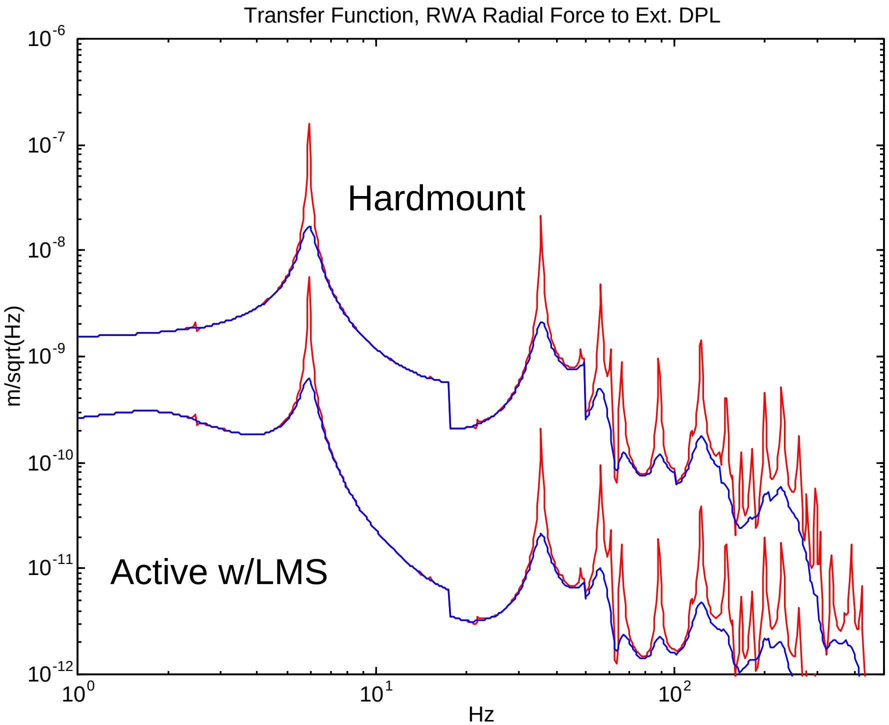
- 20 Hz, three parameter passive isolation
- Active isolation w/ first four harmonics -20dB



Input Isolation and Structural Damping

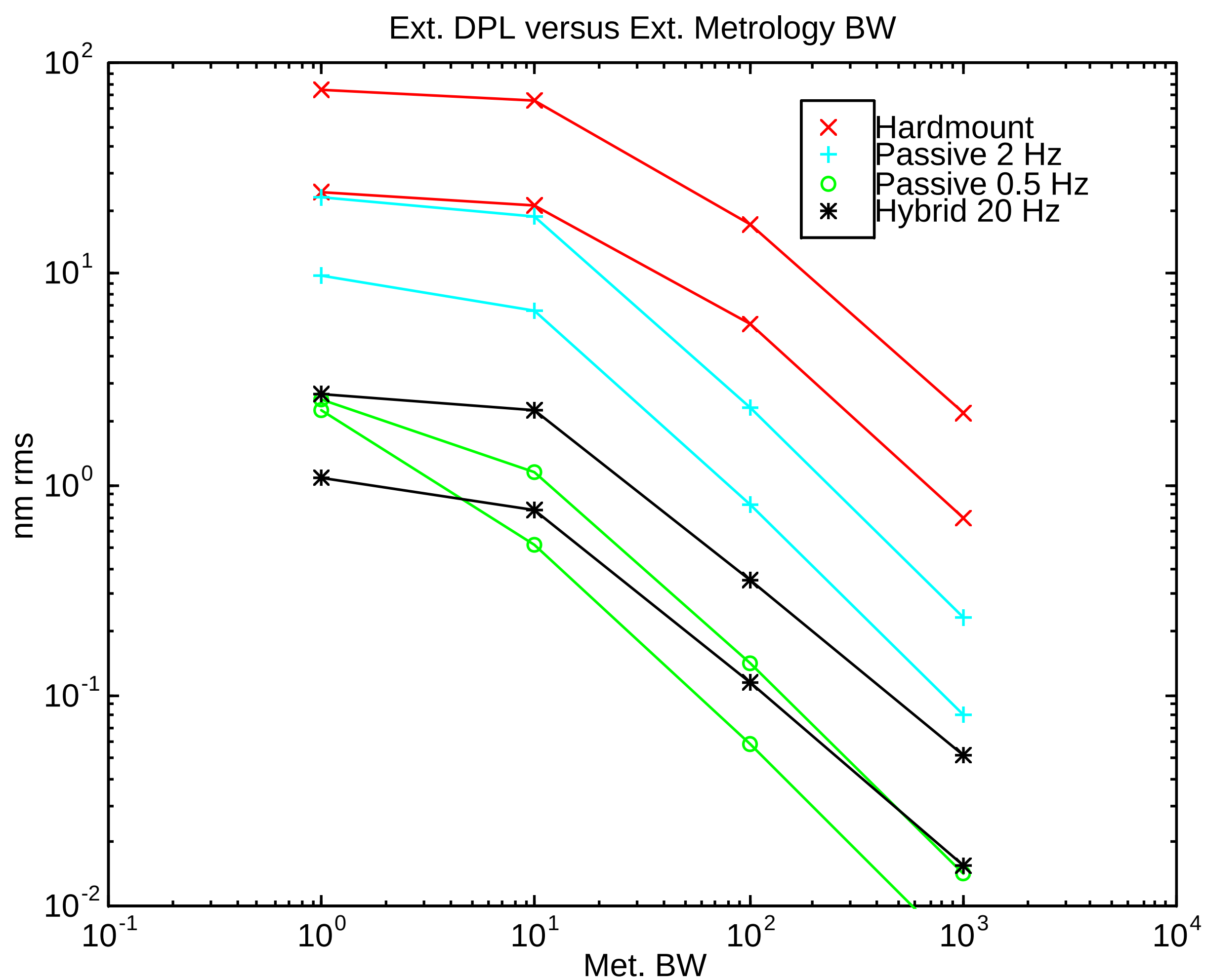


- RWA Axial Forces to Ext. DPL (Outer Siderostats Pair)



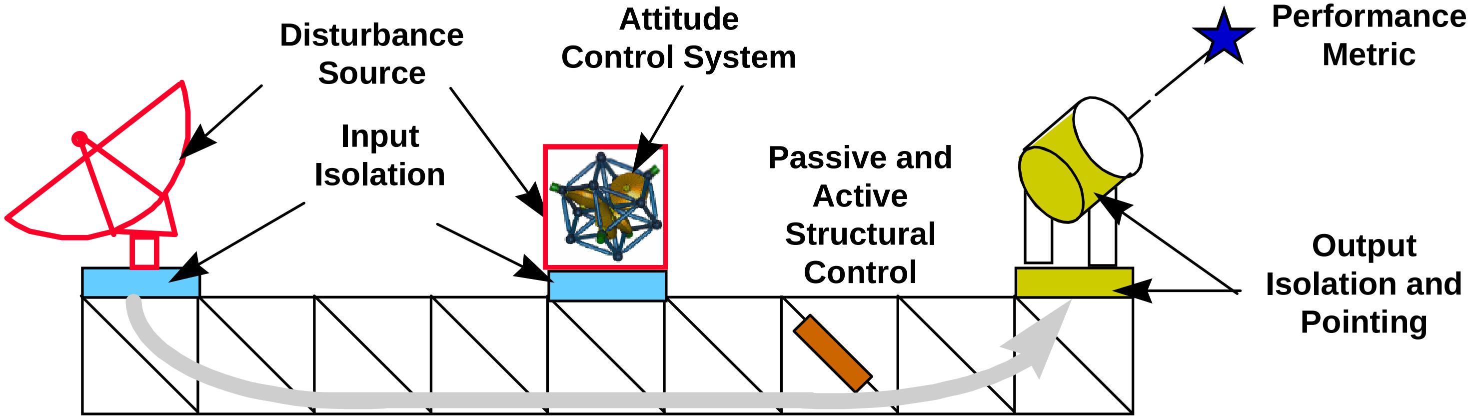
Ext. OPD (RMS 0-400 Hz)	
Hardmount	78 nm
Hardmount/damped	24 nm
Isolated	3 nm
Isolated/damped	1 nm

Output Isolation (Effect of Optical Control)

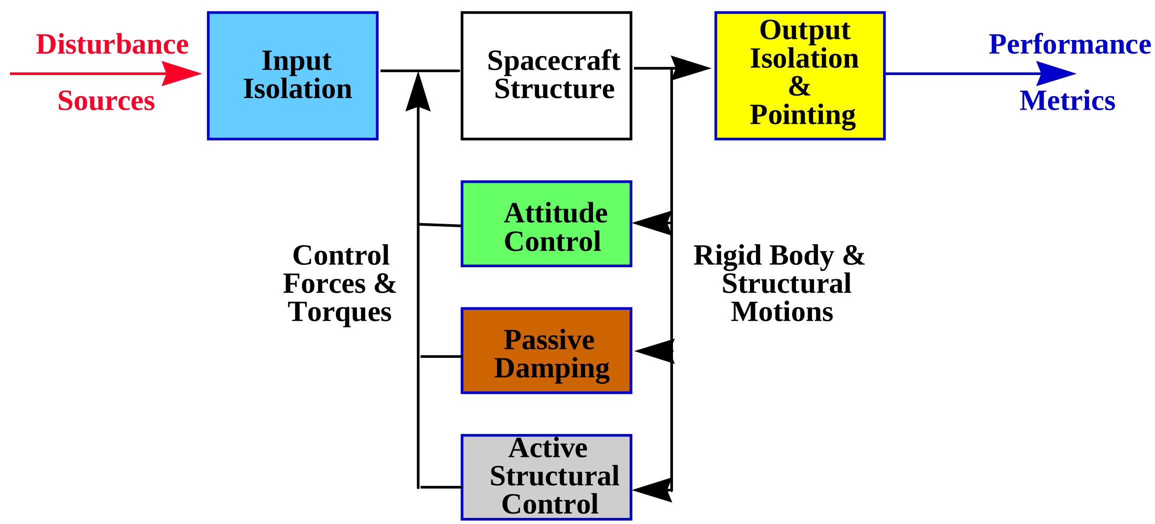


Honeywell Structural Control Testbed

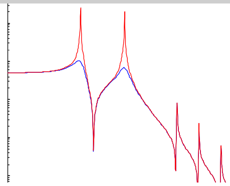
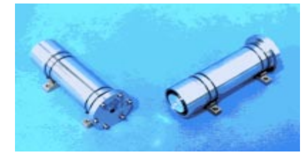
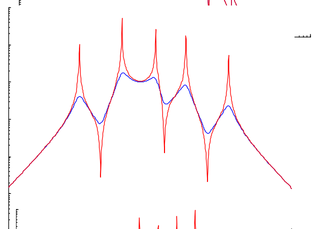
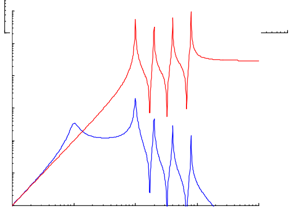
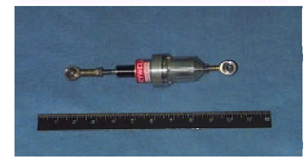
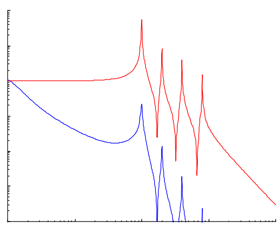
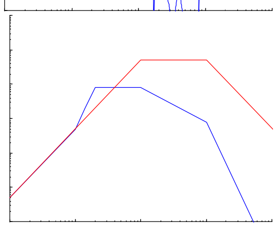
Testbed: Structural Control Toolbox Validation



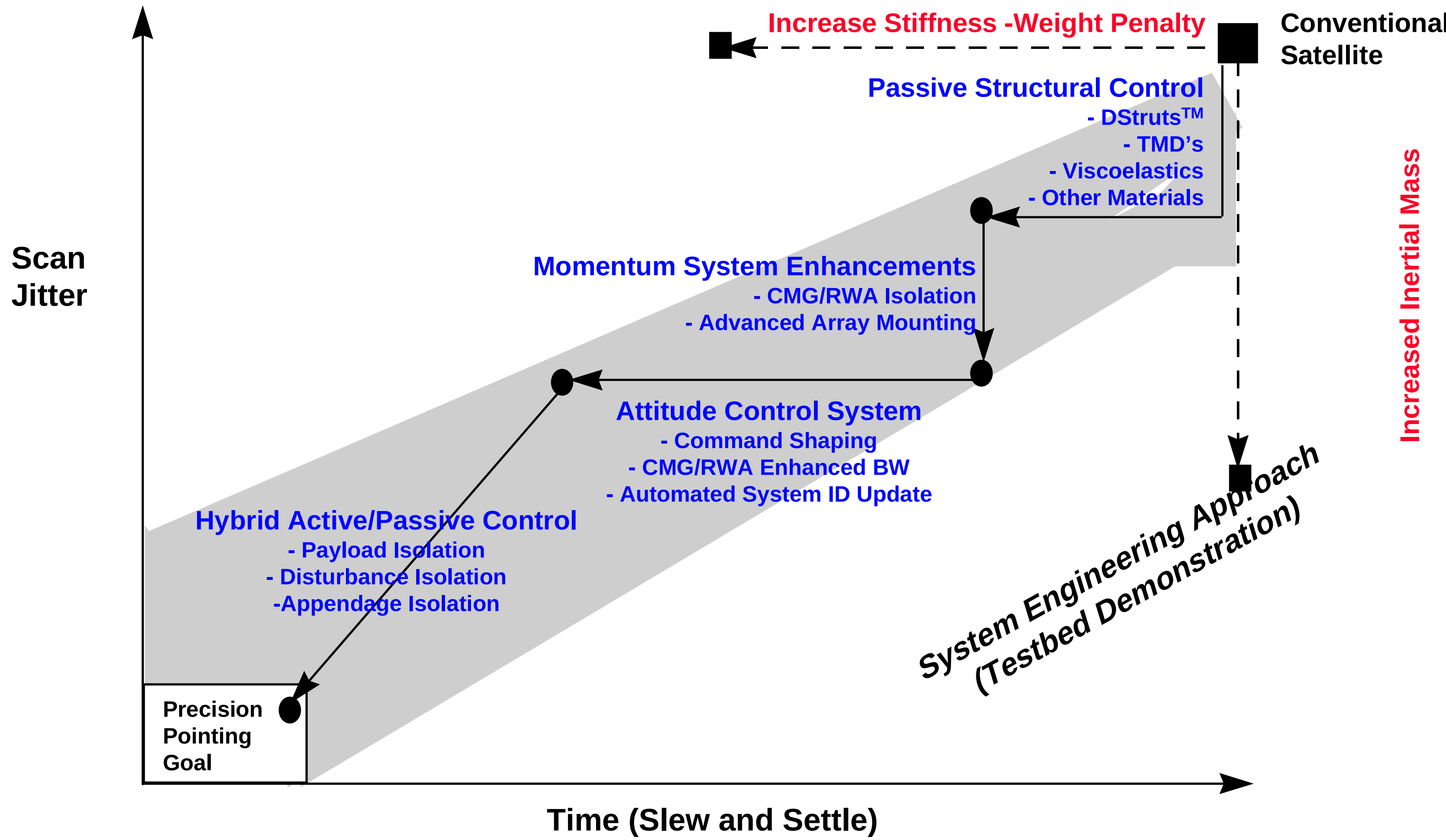
Disturbance to Performance Path



Vibration Problems and Potential Solutions

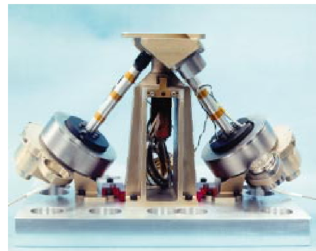
Problem	Frequency Description	Solution	Product Application
A “few” appendage modes		Honeywell Tuned Mass Damper	
Many structural resonances		Honeywell D-Strut™ Structural Damper	
High frequency base motion		Honeywell D-Strut™ Passive Viscous Isolator	
Payload disturbance and pointing, low frequency base motion.		Honeywell Hybrid D-Strut™ Vibration Isolation, Suppression and Steering System (VISS)	
Launch induced vibrations on entire spacecraft		Honeywell Launch Vehicle Isolation System (LVIS)	

Precision Agile Spacecraft Testbed Demonstration

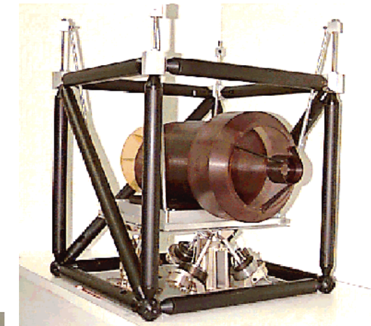


Structural Control Testbed

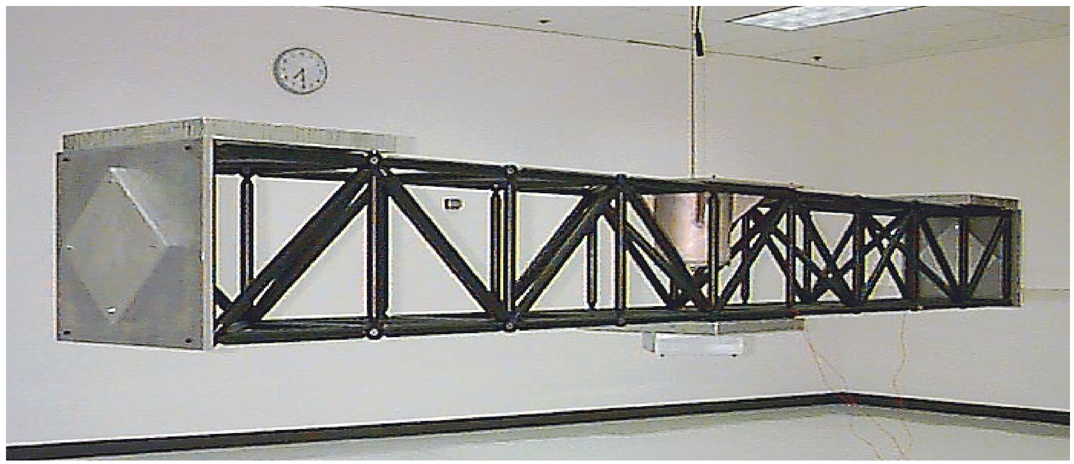
Passive Structural Control
- D-Struts™
- Tuned Mass Dampers (TMD)



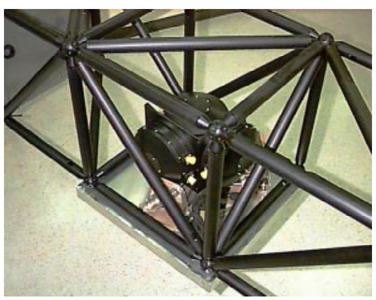
Active Structural Control
- Hybrid D-Struts™
- Proof Mass Actuators
- Fiber Optic Sensors



Precision Payload Isolation and Pointing
- VISS Hexapod
- Two-Axis Gimbal
- Inertially Stabilized Bench

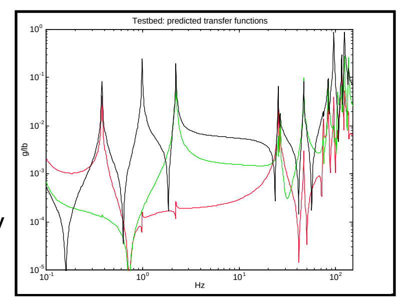


Representative Flexible Bus Structure



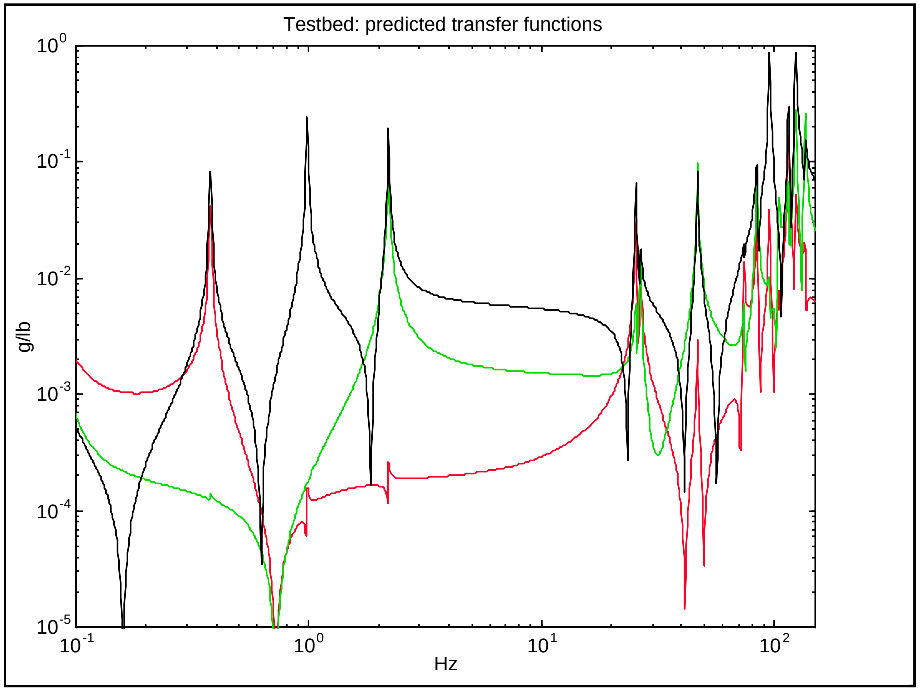
Attitude Control
- RWA/CMG's
- Momentum Systems
- GPS/IMU

Input Isolation
- Isolated RWA/CMG's
- Isolated Momentum Array
- SAD IV Reduction



Structural ID/Control
- Autonomous Identification
- Command Input Shaping
- Modern Control Theory

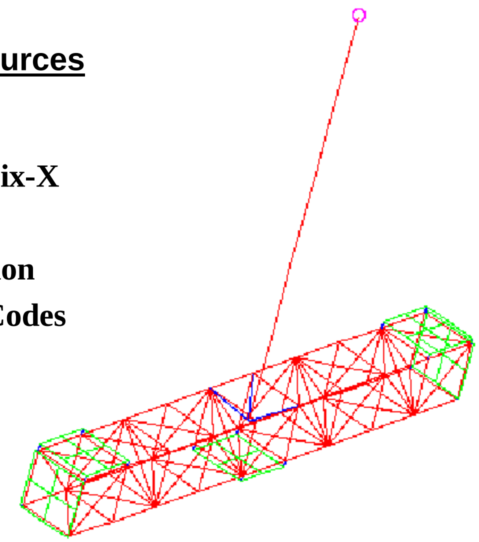
Modeling and Design Validation

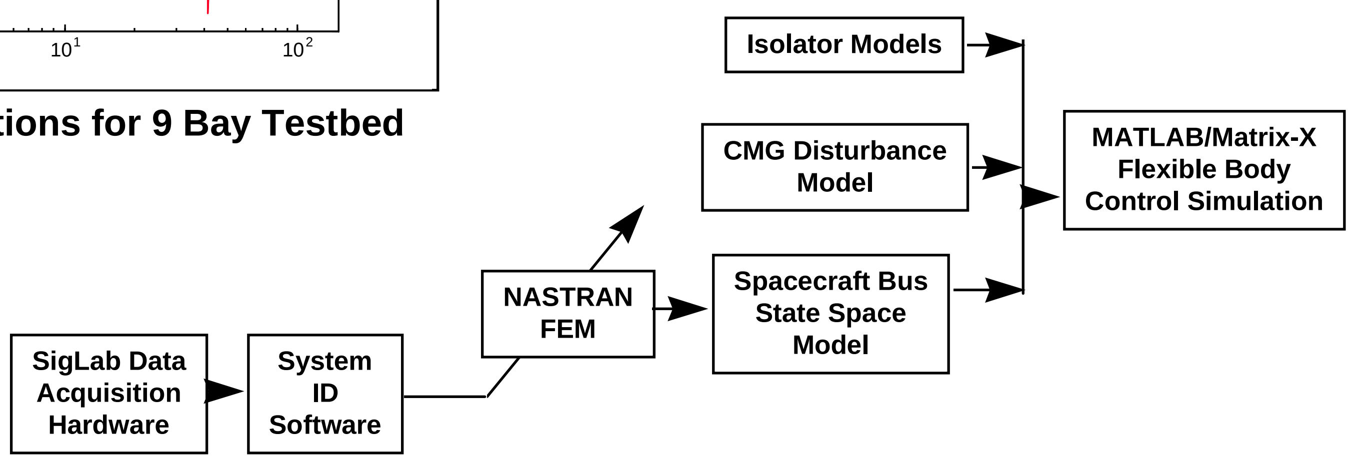


Predicted Transfer Functions for 9 Bay Testbed

<u>**Modeling Resources**</u>

- **NASTRAN**
- **Matlab / Matrix-X**
- **SDRC IDEAS**
- **Data Acquisition**
- **CMG Sizing Codes**





Launch Vibration Isolation

Launch Vehicle and Payload Interaction

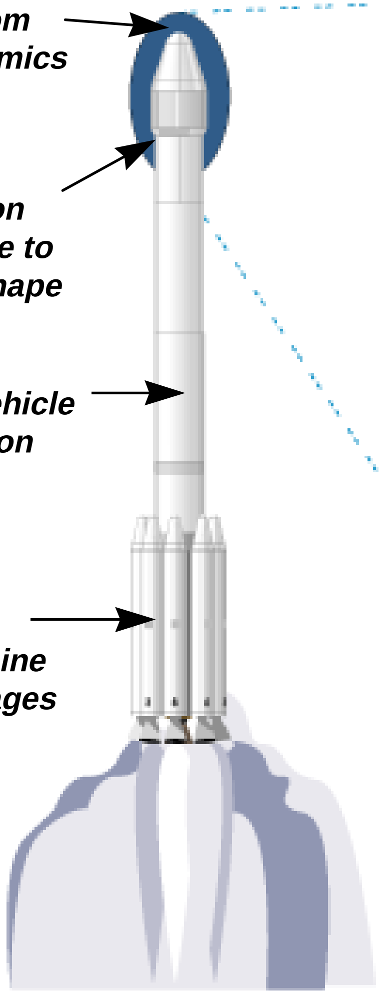
Problems

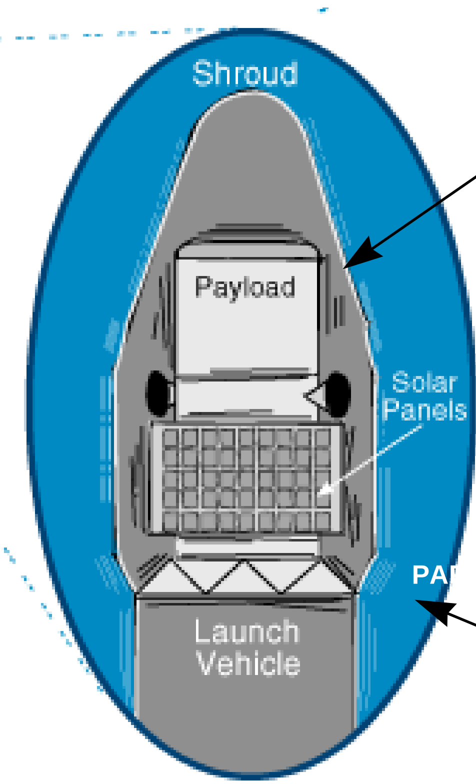
Acoustic Loads from External Aerodynamics Damages Satellite

Tight Constraints on Satellite Motion due to Fairing Size and Shape

Flexible Launch Vehicle Aggravates Vibration Loads on Satellite

Induced Structural Vibration from Engine and Separation Stages





Solutions

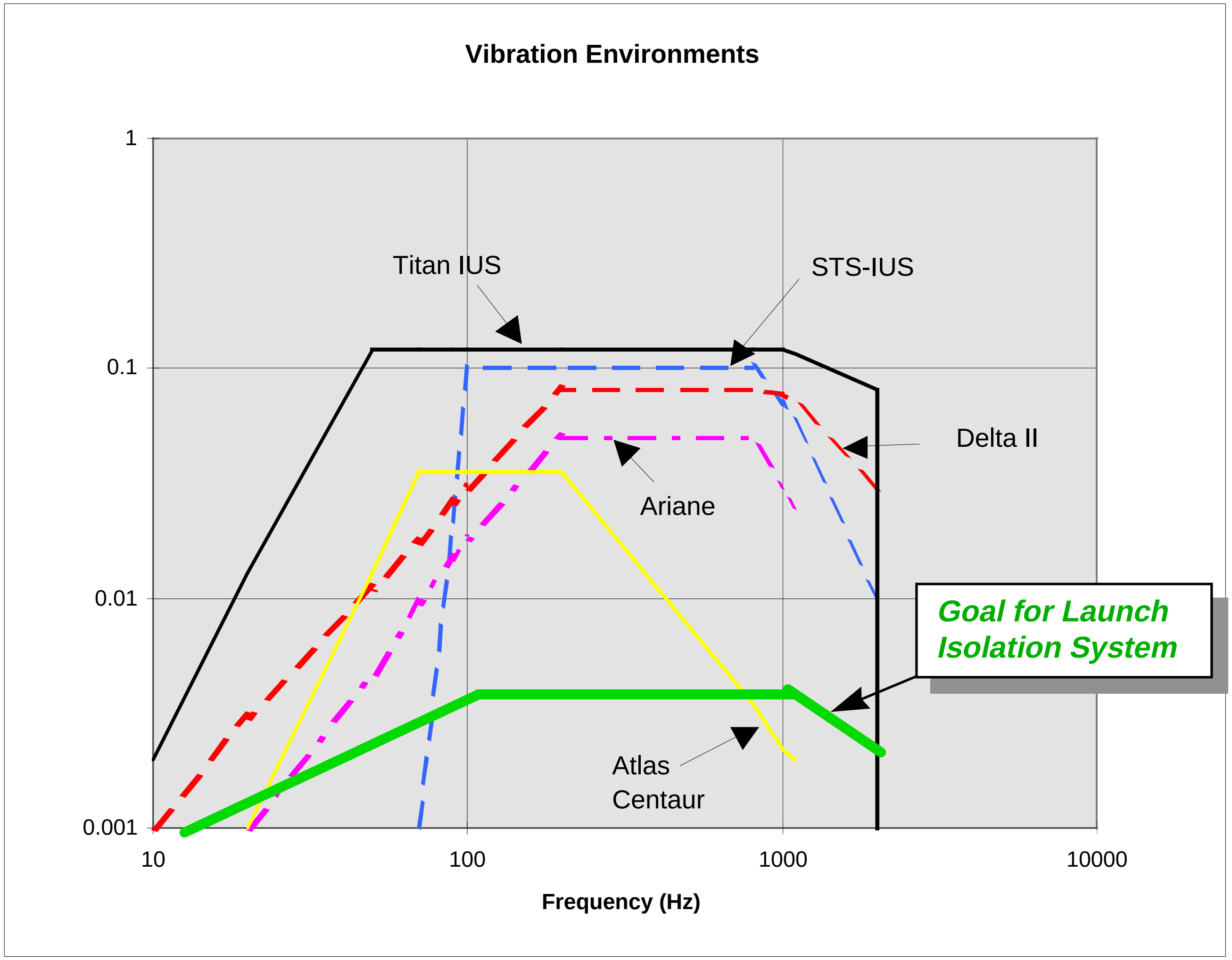
Over Design the Satellite

- Stiffen all Structure to Handle loads
- Pay weight penalty on orbit
- Pay increased bearing size penalty
- Limit size and weight by which satellite can be reduced
- Increased need for larger launch vehicles

Reduce the Environment

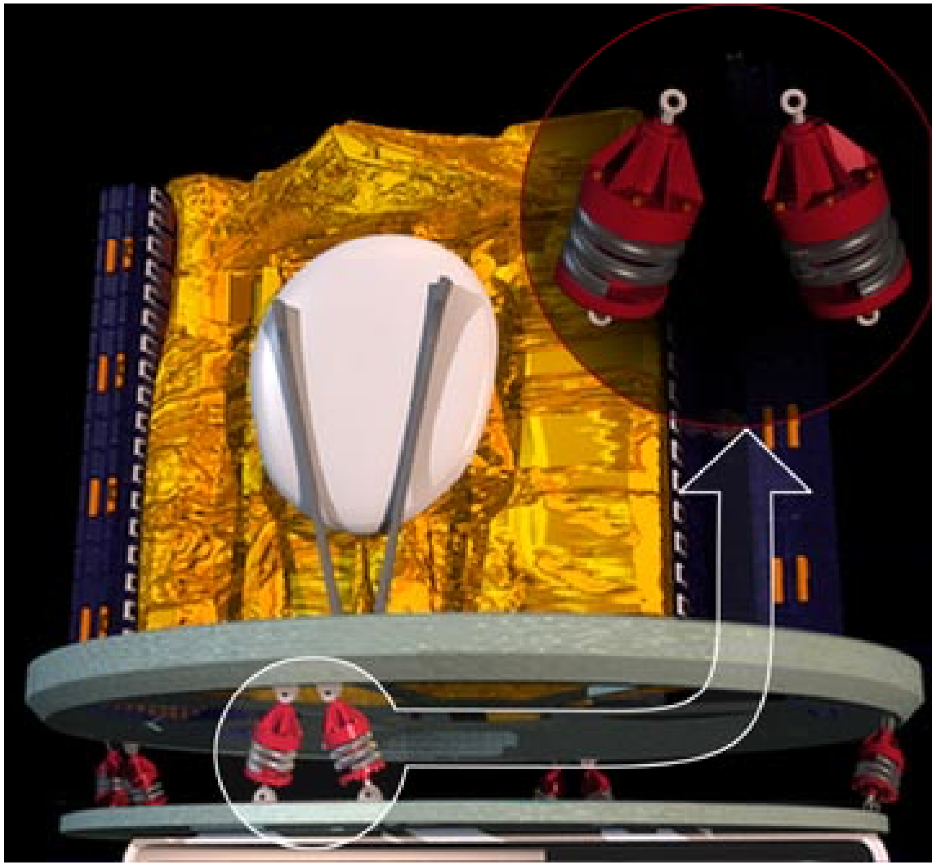
- Isolate the payload attach fitting(PAF)
- Maintain rattlespace constraints
- Reduce the axial and lateral loads
- Allow for reduced stiffness of payload
- Insure common environment across launch vehicle fleet to save cost
- Use Honeywell Patented D-Strut™ and Cross-Link Technology

Satellite Launch Load Environments



- *Variable loads on Satellite for each Launch Vehicles without standard interface*
- *Dictates individual design and qualification of each Spacecraft and Launch Vehicle combination*
- *Implies large NRE cost for large constellation deployment with more than one launch platform*

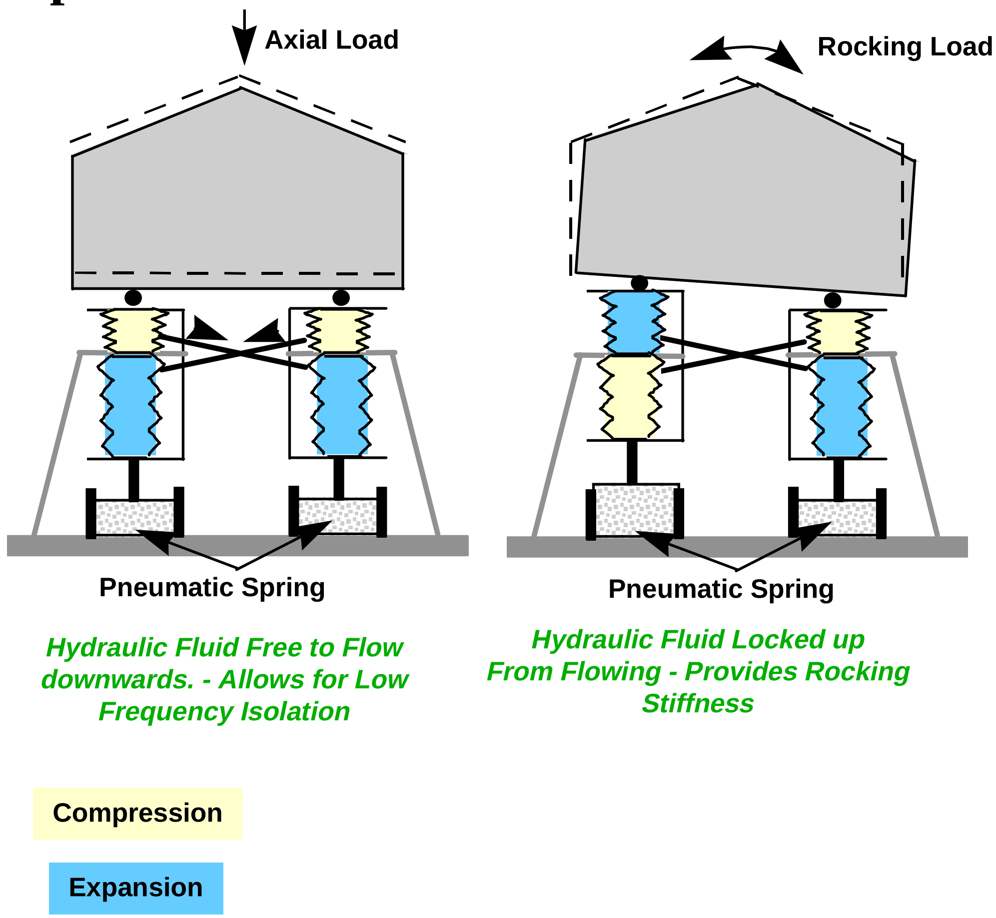
Entire Spacecraft Launch Vibration Isolation



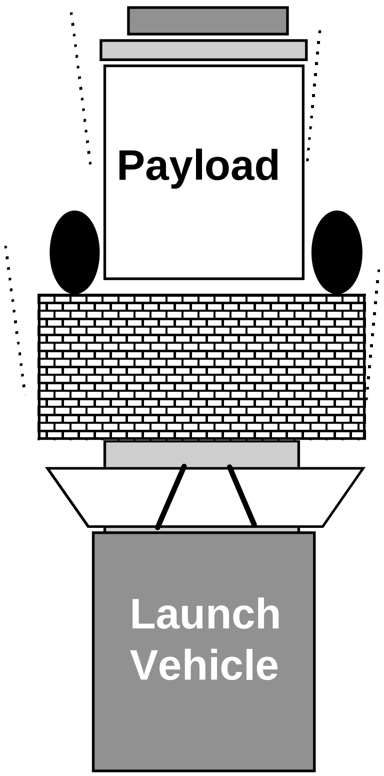
•Deterministic Multi-pod configuration
(e.g. Octapod or Hexapod)
•All 6 Degrees of Freedom Isolated
•Attenuation of Axial and Lateral Loads
•Tunable Break Frequency Design
•Easily Adapted Damping and Stiffness Parameters
•Fits Within Existing Payload Adapter Fairing Volume

Hydraulic Cross-link System

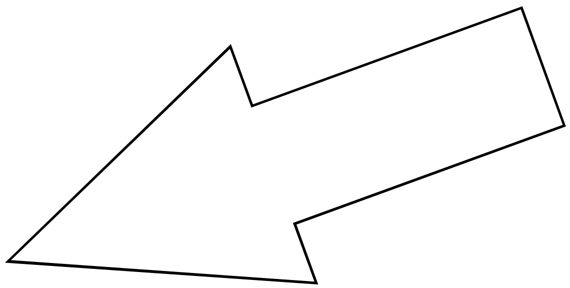
- Solution for limited lateral rattlespace
- Honeywell patented

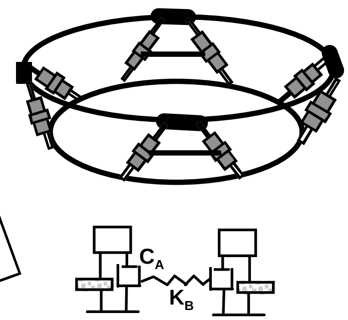


Launch Isolation Modeling



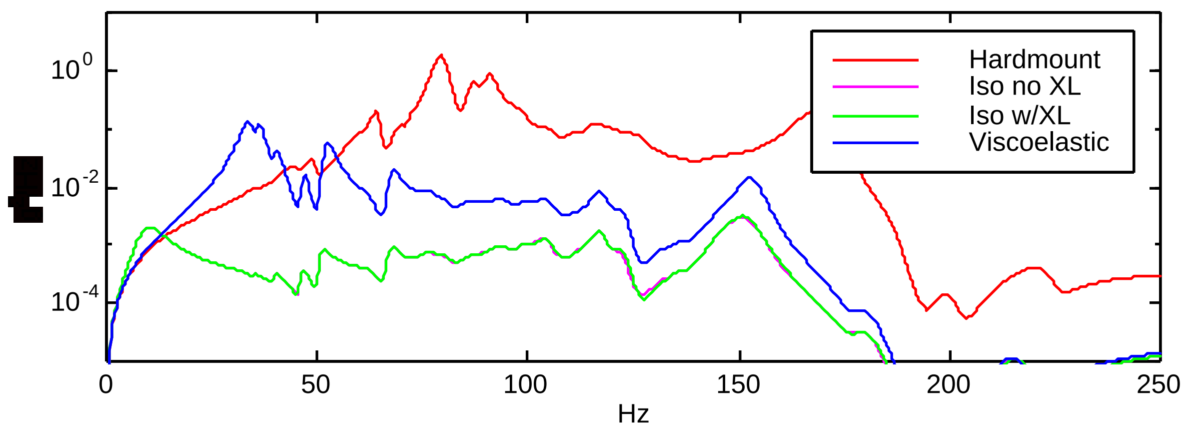
Spacecraft
and Booster
Models





Isolated PAF
Model with
Cross-linking

Simulation Results



Conclusions

- **Spacecraft are increasingly becoming precision spacecraft and the need for vibration modeling and control is evident**
- **Proper modeling of disturbances, performance metrics, and structural transfer is key to the system engineering approach to vibration control**
- **Input isolation, passive and active structural control, and output isolation & pointing are the tools used to meet vibration performance goals**
- **Vibration isolation of the entire spacecraft from launch loads can significantly reduce spacecraft cost and weight**
- **Flight qualified hardware exists to implement each of these solutions**